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REFERENCE

Lane, B. H., 1935. Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C., 25c.)

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FEBRUARY 1952

MOUNT GARIBALDI, A SUPRAGLACIAL PLEISTOCENE VOLCANO IN SOUTH-WESTERN BRITISH COLUMBIA

W. H. MATHEWS

ABSTRACT. Mount Garibaldi is an extinct volcano built for the most part by glowing avalanches during an almost uninterrupted series of Peléan eruptions. A dacite core and lava flows from a vent on the northern slope make up the remainder of the mountain. A large volume of debris from the western slope of the cone now lies in nearby Squamish Valley as fanglomerate and late Pleistocene to Recent alluvium. Despite the loss of enormous quantities of material from this side of the cone, part of the original upper surface persists in an adjoining sector. Tuff-breccias laid down by the glowing avalanches do not extend as far from the apex of the cone down two pre-existing valleys as they do on an intervening ridge. The cone was built during occupation of the valleys by Cordilleran ice of Wisconsin age and part of it was evidently deposited on the ice. Ice filling the old valleys may have prevented extension of the glowing avalanches beyond the limit reached on the intervening ridge which then protruded only a little above the ice surface. Melting of the ice in late Wisconsin time permitted extensive landsliding and transfer of debris from the cone to Squamish Valley.

INTRODUCTION

MOUNT Garibaldi, one of the largest of a chain of relatively small volcanoes in the southern Coast Mountains of British Columbia (see also Mathews, 1951), is situated 40 miles north of the city of Vancouver (fig. 1). Size alone does not make this volcano noteworthy, but the excellent exposures of its internal structure as well as striking abnormalities in its present topography command the attention of the geologist. If, as the evidence indicates, the volcano came into being during the time of occupation of the Pleistocene ice sheet and was built partly on the ice, it is unique among volcanoes now described in the geological literature.

As the petrographic characters of the products of this volcano bear much in common with those of other volcanoes in the same chain, discussion of these characters is deferred

for another paper, and the present discussion is restricted as far as possible to megascopic features bearing directly on the origin of Mount Garibaldi.

DESCRIPTION

Introduction. —Mount Garibaldi is a composite volcanic mass consisting of a partly destroyed cone of tuff-breccia, a core of intrusive dacite, and a veneer, on its northern slope, of lava (fig. 2). An enormous volume of volcanic detritus, both fanglomerate and alluvium, clearly derived from Mount Garibaldi, lies along the eastern side of Squamish Valley (fig. 3), several miles west and southwest of the mountain.

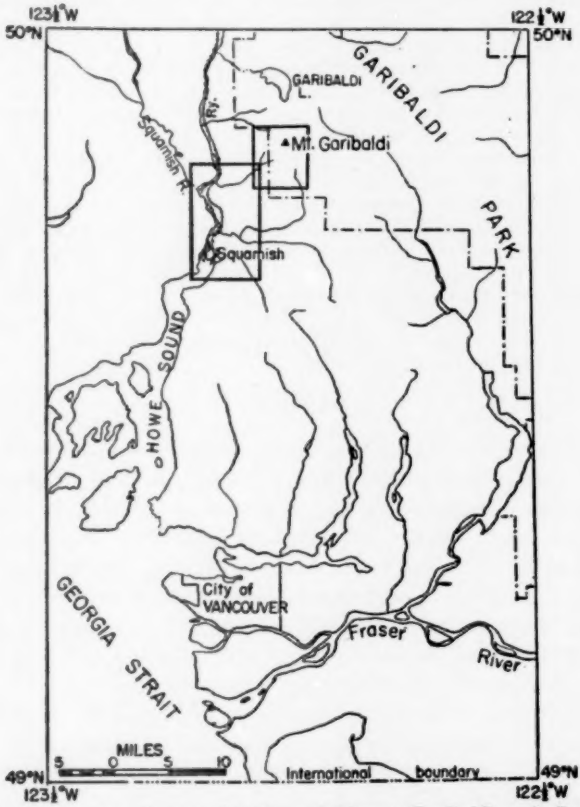

Fig. 1. Index map showing location of Mount Garibaldi and Squamish Valley.

Some dune-like deposits of volcanic dust on the ridge 2 miles west of the summit of Mount Garibaldi (fig. 2) may also be products of the activity of this volcano. Prior to the eruptions, a foundation of Mesozoic (?) metamorphic and plutonic rocks had been carved into a rugged surface with a relief of approximately 6,000 feet.

Tuff-breccia cone.—Pale red, pale green, and light gray tuff-breccias are exposed in an area of about 3.5 square miles south and southwest of the summit of Mount Garibaldi to depths of as much as 2,300 feet. Similar tuff-breccias are interbedded with lava on Brohm Ridge, to the west, but it is uncertain whether these were derived from eruptions of Mount Garibaldi and, if so, whether they are contemporaneous with those farther south and east. Because of this uncertainty the volcanic rocks of Brohm Ridge are not included in the description of the Mount Garibaldi tuff-breccias.

Typical tuff-breccia on the slopes of both Mount Garibaldi and its subsidiary peak, Diamond Head, consists of volcanic debris ranging in size from dust to enormous blocks. A mechanical analysis of a small amount of the tuff-breccia, apart from demonstrating extreme lack of sorting, revealed only that the peak diameter of the fragments exceeded 6 centimeters. The debris is virtually unconsolidated, and many of the larger blocks can be dislodged by careless footsteps or falling stones. Chemical analysis shows that the tuff-breccia is of dacitic composition.

Angular, generally more or less equidimensional blocks, are distributed throughout the deposit. A few of these exceed 20 feet in diameter and one measures 55 feet across. Many blocks, both large and small, display flow-banding truncated by the present surfaces; evidently these were derived by fragmentation of a larger, banded, igneous mass. Some blocks have reddened rims resulting from oxidation after fragmentation, at temperatures of many hundreds of degrees centigrade. Many have radial contraction cracks, some of which are so deep that the blocks are on the point of falling apart or have already done so. Such cracked blocks must have reached their present locations before being completely cooled; their temperatures may have dropped several hundred degrees during and after transportation.

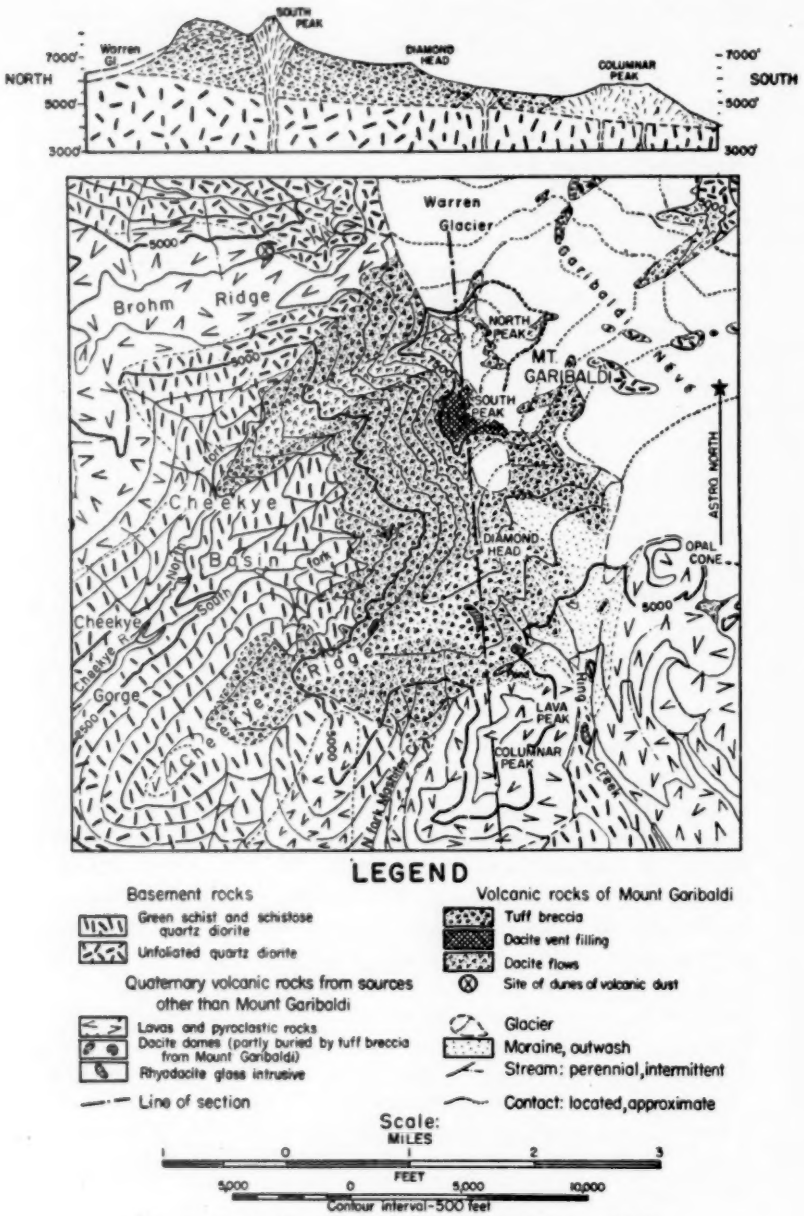

Fig. 2. Geological map of Mount Garibaldi and vicinity.

Stratification, poorly defined but nonetheless unmistakeable, is revealed on any large exposure, notably on the cliff faces at the head of the south fork of Cheekye River. It results from a succession of layers differing in the relative proportions of coarser fragments and, in a very few places, from differences in color, resistance to erosion, and permeability to ground water. Throughout the tuff-breccia cone the bedding dips radially outward at about 10° to 15° from the intrusive mass forming the south peak of Mount Garibaldi.

One interruption in the succession of tuff-breccias is detectable. This is an erosional disconformity about midway up the cliff face at the head of the south fork of Cheekye River. At least several tens of feet of beds were eroded from the lower part of the succession before the younger beds were laid down. The absence of any other disconformity in this part of the deposit indicates that all the tuff-breccias, which are here about 2,300 feet thick, were laid down during only two relatively continuous eruptive episodes. The deposits of these two episodes make up the greater part, and perhaps all, of the tuff-breccias within and adjacent to Mount Garibaldi. Possibly, however, some of the pyroclastic rocks on the northwestern slope of the mountain, which are distinctly lighter in color, are products of one or more later eruptions.

The mode of origin of the tuff-breccias is readily apparent. Their source lies in the banded lava of the central dacite mass now forming the south peak of Mount Garibaldi. Brecciation of this dacite as it emerged at the surface accounts for the fragmental texture of the deposit surrounding it; transportation of the debris across the slopes of the growing cone in the form of hot avalanches accounts for the stratification dipping at low angles away from the source. Judging from the reddened crusts on the fragments and from the numerous contraction cracks the material moved in a very hot and almost certainly dry condition. Similar flows of dry, hot fragmental debris of volcanic origin are well known since the eruptions of Mount Pelée in the West Indies in 1902 (Lacroix, 1904; Anderson and Flett, 1903) and in 1929-1932 (Perret, 1935). The detailed field and petrographic descriptions of the debris on the Soufrière Hills of the Island of Montserrat (MacGregor, 1938), which resembles that on the slopes of Mount Pelée, could be used almost without change for the

tuff-breccias of Mount Garibaldi, and photographs of the deposits of both Montserrat and Mount Pelée could be duplicated on the British Columbian volcano.

The terms "glowing avalanche," "lava discharge of the Peléan type," and "*nuée ardente*" have been applied to moving masses of hot fragmental lava such as accompany eruptions of Mount Pelée. The last of these terms, though the most familiar, seems the least appropriate for activity which gave rise to thick and extensive sheets of tuff-breccia. Perret, following Lacroix, uses the term *nuée ardente* to embrace all the phenomena accompanying lava discharge of the Peléan type, but he, like Anderson and Flett, clearly distinguishes the *avalanche* itself from the accompanying *cloud*. The avalanche, he notes, is deflected by irregularities in the underlying topography but the cloud may sweep across valleys and low ridges alike. The avalanche leaves a deposit of assorted fragments, many of enormous size, but the cloud itself carries only finer particles. "Peléan tuff-breccia" or "glowing avalanche debris" are, for obvious reasons, preferable to "nuée ardente deposit" which could be interpreted as the products of both avalanche and cloud, or, if translated literally, of the hot cloud alone. Under no circumstances could the material in Mount Garibaldi be described as "welded tuff," for it is neither sufficiently fine grained to be called a tuff, nor is it in the slightest degree welded.

The surface on which the tuff-breccias now rest is extremely irregular, ranging in altitude from 3,000 feet on the north fork of Cheekye River to 5,600 feet near Diamond Head. Continuous valley-slopes, formerly buried by tuff-breccias and now partly exposed by erosion, extend from 5,200 feet down to 4,100 feet at an average gradient of more than 20 degrees on the south wall of Cheekye Basin. This basin and Cheekye Gorge must have been excavated to within a few hundred feet of their present depths before deposition of the tuff-breccias. The northern base of Lava Peak is partly buried by the debris. Several dacite masses north of Lava Peak were completely buried by tuff-breccias and only their summits have since been exposed. The tops of the central and northwestern domes bear striations which trend south 30° east and south 30° west respectively, parallel to the dip of the adjacent tuff-breccias. Certainly the striations at the former

locality are to be attributed to abrasion by the glowing avalanches rather than to erosion by ice which here flowed southwesterly.

A conspicuous zone of alteration occurs immediately beneath the tuff-breccias where greenish schistose quartz diorites have been converted into silvery or iron-streaked schists and rusty clays. This zone can be seen at many points along the contact on the south wall of Cheekye Basin. Alteration extends into the older rocks to depths of a few feet on the higher slopes of the basin and to as much as 20 feet near the valley bottom. Oddly enough neither the tuff-breccias themselves nor the buried dacite domes exhibit this alteration. The altered rocks cannot be old weathering products preserved from erosion beneath the tuff-breccias, for they are present on slopes too steep for development of soils of such thickness, and they are restricted to areas once, or still, covered by tuff-breccias. Indeed the only other localities within a 380 square mile area surrounding Mount Garibaldi where similar alteration has been noted are: (1) under similar tuff-breccia on the south rim of Brohm Ridge, (2) adjacent to a dike 2 miles northeast of the north peak of Mount Garibaldi, and (3) on the footwall of a rhyodacite intrusion at the eastern base of Lava Peak. Similar alteration is unknown under the lava flows, just where conditions would be especially favorable for preservation of old soil. Accordingly the alteration seen on the south wall of Cheekye Basin must be attributed to the tuff-breccias of Mount Garibaldi with which it is so closely associated in spatial distribution.

A sample of clay was taken from the altered zone at an altitude of 4,500 feet on the south fork of Cheekye River. That part of the sample made up of particles smaller than a micron was examined by Dr. I. Barshad of the Division of Soils at the University of California. On the basis of X-ray and differential thermal analyses, together with measurements of base exchange capacities, he reports that between 30 and 50 per cent of the material is made up of an expanding-lattice type mineral similar to montmorillonite or vermiculite, between 15 and 30 per cent is made up of a hydrous mica, and between 35 and 40 per cent of kaolinite or halloysite. Oxidation of pyrite, in the green schistose quartz diorites as well as in the clay, accounts for the conspicuous orange

to brick red color of the alteration zone. Magnetite is locally abundant.

Because the depth of alteration is greater near the bottom of the buried valley than higher on its walls, it can be concluded that alteration has been effected by descending waters which were more abundant or more active near the base of the tuff-breccia deposit. No lines of intense alteration such as might be attributed to old watercourses along the schist-tuff-breccia contact were observed; instead, a more or less uniform percolation of waters through the tuff-breccias and along the schist surface seems to be indicated. Presumably meteoric water soaking through the tuff-breccias shortly after their deposition became heated and charged with dissolved gases and salts thus becoming an active agent in the chemical attack of the highly fractured schists. Conceivably, however, vapors given off directly by the tuff-breccia were responsible for the alteration and because of either lower gas pressure or quicker escape at shallow depths the alteration was less intense here than at lower levels. In either event, alteration presumably took place before the tuff-breccias became cold. Whether or not the schists had previously been rendered permeable by weathering is no longer determinable. Because of their relatively stable mineralogical composition or imperviousness, the buried dacite domes resisted alteration.

The present topography of the tuff-breccia deposit deserves mention. Although a stratigraphic thickness of more than 2,000 feet of pyroclastic rocks is exposed on the west face of Diamond Head, the original surface of the volcanic cone appears to be preserved on the south slope of this same peak. Moreover there are local irregularities on this surface which do not appear to have originated during the normal processes of accumulation of tuff-breccias.

What seems to be part of the original surface of the cone is well preserved in a triangular area, about a third of a square mile in extent, south and southwest of Diamond Head. Only locally has it been modified by erosion. Over the greater part of its area, the surface slopes evenly southward at angles of 12° to 15°, approximately parallel to the underlying stratification. Near the summit of Diamond Head, however, the slope is distinctly greater and the bedding is truncated at an acute angle by the present surface. The junction of

this part of the surface and the more gradual slope below is not clearly defined but is situated near the 6,000 foot contour. Deep stream-cut ravines are present only at the lower edge of the area, around the head of the valley of the north fork of Mashiter Creek, and at its eastern margin, adjacent to the valley of Ring Creek. Only shallow watercourses are present in the central part of the area, and except at the period of most rapid melting of snow during the early summer months this part of the slope is free from surface waters. The high permeability of the tuff-breccias has apparently been responsible for the comparative freedom of this surface from stream erosion.

This gently sloping surface falls away abruptly, slightly less than a mile southwest of Diamond Head, into the valley of the north fork of Mashiter Creek. This change in slope takes place at altitudes varying from 5,200 to 5,600 feet. Though stream erosion has partly dissected the face of the tuff-breccia deposit, abundant relics of pyroclastic debris occur at lower levels for somewhat less than half a mile south of the rim of the scarp; beyond, they are conspicuous by their absence. No traces of tuff-breccia can be found on the slopes of the valley more than 9,000 feet southwest of the summit of Diamond Head even at points hundreds of feet below the projected upper surface of the deposit. Apparently, no debris was laid down by glowing avalanches in this valley more than 2½ miles from the source in the south peak of Mount Garibaldi, and the steep tuff-breccia face at the head of the valley must be interpreted as a partly modified original surface.

Close to the crest of Cheekye Ridge, about 2 miles southwest of the summit of Diamond Head, the surface of the tuff-breccias is broken by numerous sub-parallel scarps and troughs that vary from a few tens to several hundred feet in length and have a local relief of up to 35 feet. They trend consistently south 30° west and are rarely more than 250 feet apart. Several troughs are closed depressions; of the others, some drain to the north slope of Cheekye Ridge, some to the south slope, and a few on the crest of the ridge drain in both directions. A few troughs branch, but most are simple. The height of a scarp or of the walls of a trough varies gradually from place to place, and wherever it is less than

a foot or two the identity of the feature becomes lost amid minor irregularities of the surface. The termini of one scarp or trough seem to bear no consistent position with respect to those of neighboring scarps or troughs. If the scarps and troughs were parallel to the slope, a landslide-origin might be considered, but their oblique trend across the slope and their development on both sides of the ridge crest discredits such a simple hypothesis. They were not developed by normal processes of erosion for these would hardly produce closed depressions. The features in question are only to be seen among the tuff-breccias on or close to the crest of Cheekye Ridge and they are not known to have developed on any other type of rock. Whatever their origin, they almost certainly date back to the time when the tuff-breccias come to rest in their present position.

The western slopes of Diamond Head and Mount Garibaldi, which extend down into Cheekye Basin, clearly truncate the bedding of the tuff-breccias and just as clearly were developed after deposition of the pyroclastic deposit. Numerous gullies score the slope in the fine textured pattern characteristic of badlands. Individual blocks falling from the tuff-breccia of the upper parts of the mountain, by dislodging others, create showers of rock which constitute the most obvious mechanism of mass wasting. Concentration of the rock showers in the gullies may be responsible for the preservation of these features, if not for their enlargement. Only near the bottom of the slope, where semi-permanent streams exist, does water appear to be an important agent in the transportation of waste. Notwithstanding the rapid rate of disintegration of this slope of the mountain, the volume of material missing from the cone-shaped pile of tuff-breccia which presumably existed at the time of the eruptions is surprisingly large. The fact that beds more than 2,000 feet below the original surface of the tuff-breccia deposit are exposed on this slope of Diamond Head while the original surface exists on the adjoining slope is equally surprising.

The eastern slope of Diamond Head and the adjoining southeastern slope of Mount Garibaldi present much the same appearance as does the western face. On this eastern side, however, a small glacier nestles at the base of the steep slopes, and ice transport, rather than stream transport, is chiefly responsible for the removal of waste.

The northern and northeastern parts of the tuff-breccia deposit are almost entirely concealed by later lava or by glacial ice and the characteristics of its upper surface cannot be determined.

Dacite core.—The dacite mass forming the south peak of Mount Garibaldi is exposed over an area measuring half a mile from east to west and almost as much from north to south. Its southern limit is clearly defined and reasonably accessible; its western and northwestern limits, high on the precipitous west face of Mount Garibaldi, are readily visible from a distance but virtually unapproachable; its northern limit is accessible at only one point, on the summit arête; its northeastern and eastern limits are concealed by the Garibaldi névé. The only rocks with which the core is in contact are the tuff-breccias previously described.

Originally, the core was wedge-shaped or funnel-shaped, judging from the steep inward dips of the flow banding at the northern and southern margins. The original upper surface of the tuff-breccias, if projected northward from Diamond Head parallel to the bedding, passes within a few score feet of the present summit of the south peak, and the solid dacite presumably rose above this surface like the plug dome of Mount Pelée. Masses of tuff-breccia, 100 feet and more across, are sandwiched between walls of solid dacite on the summit ridge; these may have been formed by disintegration of dacite in and above gaping fissures in a rising column of lava. As such masses of tuff-breccia were presumably formed close to the original surface of the plug dome, this surface must have been situated not far above the present summit of the south peak. Wasting of the surrounding tuff-breccia into Cheekye Basin on the one side and onto the glaciers near the head of Ring Creek on the other has exposed parts of the dacite which formerly lay fully 1,000 feet below the surface.

Lava flows.—The northern part of Mount Garibaldi is mantled by dacite flows that radiate from the plateau near its northern peak. This plateau, partly surrounded on the north and west by higher ground, may mark the crater from which the flows were extruded. One flow extends uninterruptedly for several thousand feet down the western face of the mountain, at an average slope of about 35 degrees, resting

on a surface which truncates the more gently dipping tuff-breccias. Several superposed flows, dipping northeastward at angles of 30° to 35°, form the highest point on the mountain. Other flows covering the lower northern and eastern slopes may have issued from the same or nearby sources, but the present cover of glacial ice obscures the relationships.

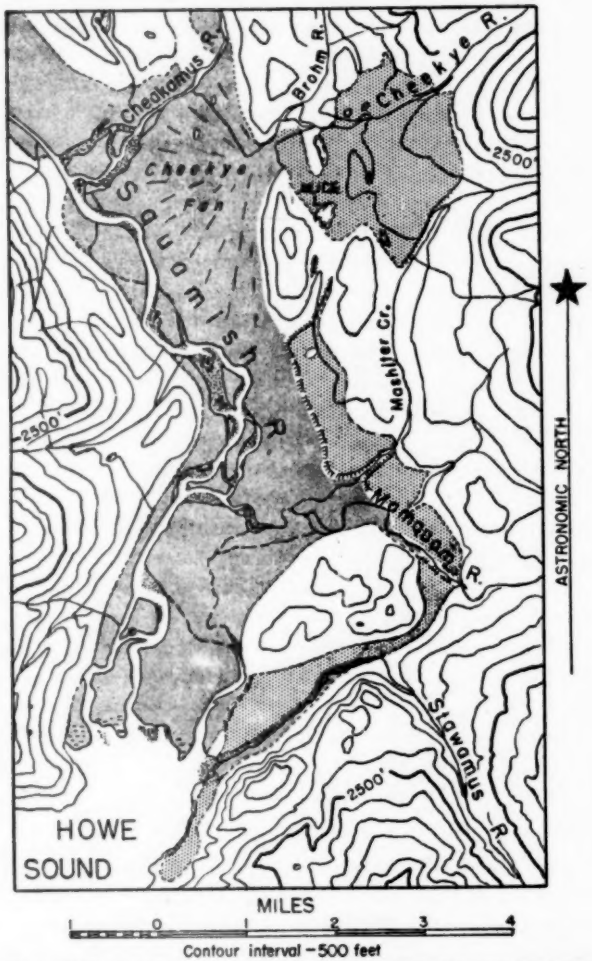

Fig. 3. Map of Squamish valley. Terraced fanglomerates and fluvioglacial debris indicated in coarse stippling. Recent alluvium indicated in fine stippling.

Volcanic detritus of Squamish Valley.—A very large volume of volcanic detritus from Mount Garibaldi now lies along the eastern side of Squamish Valley, notably in the Recent fan of Cheekye River, in a series of terraced fans farther upstream, and in a chain of fluvio-glacial deposits extending for several miles south from Cheekye River.

The Recent fan of Cheekye River covers about 4.4 square miles. Its surface slopes from about the 500 foot level on the east to the banks of the Cheakamus and Squamish Rivers on the west, about 100 feet above sea level. The depth of the deposit is uncertain as no wells have been drilled to bedrock; however, only two small bedrock hills protrude through the deposit and these lie near its northern margin. Inasmuch as the bedrock relief in nearby areas of similar size exceeds several hundred feet, it may be that the fan itself attains a similar depth. The detritus making up the fan consists principally of coarse gravel in which red to gray dacite, typical of the Mount Garibaldi tuff-breccias, predominates. Boulders of resistant quartz diorite, which is exposed in about 40 per cent of the Cheekye drainage basin, are conspicuous locally, notably below the junction of Cheekye and Brohm Rivers. Construction of the fan has gone on at such a rate in post-Pleistocene time that Cheakamus River, to which the much smaller Cheekye River is tributary, has been forced against bedrock on the western side of its valley and has been sufficiently dammed to aggrade Cheakamus Valley for about 6 miles upstream. This rapid growth of the Cheekye fan offers independent evidence of the rapid rate of erosion of the tuff-breccias on the western slope of Mount Garibaldi which provide most of the debris carried by Cheekye River.

A terraced deposit of fanglomerate covers almost 3 square miles on both sides of Cheekye River between the area of Recent sedimentation on the floor of Squamish Valley and the steep eastern valley wall. Deep cuts along Cheekye River show that this deposit has in places a thickness of at least 400 feet and, like the Cheekye fan, it effectively conceals bedrock everywhere except near the margins. The upper limit of the fanglomerate, at the mouth of Cheekye Gorge, lies at an altitude of about 1,700 feet. From this point, the surface of the highest fan slopes radially outward at angles of between 5° and 7°. This surface terminates about half a mile

away in a moderately steep and irregular west-facing slope. Lower terrace surfaces also slope outward from the mouth of Cheekye Gorge, and these, too, terminate in irregular west-facing declivities. Several kettles, a few of them occupied by small lakes, break the continuity of the terrace surfaces in these western parts. A terrace surface in the valley extending southward from Alice Lake is represented by only two narrow discontinuous fringing shelves at concordant levels on opposite walls of the valley several hundred feet above its floor.

The material making up the terraced fan deposit is composed exclusively of dacite debris showing the same lithologic characters and a similar lack of sorting as the tuff-breccias of Mount Garibaldi. Boulders up to 6 feet in diameter have been observed in the fanglomerate, but very large blocks, like those seen on the slopes of Mount Garibaldi, are absent. Breadcrusted and reddened surfaces and radial fractures are not conspicuous on these boulders as they are on the blocks in the tuff-breccia. Throughout most of the fan deposit stratification is completely absent, but in a few places relatively thin, sharply defined beds of fine material may be seen. These beds generally lie parallel to the top surfaces of the terraces even where these are pitted.

The mode of origin of the terraced fan deposit is clear. The detritus was derived from tuff-breccias on the western slope of Mount Garibaldi and was swept through Cheekye Gorge to its present location. Water presumably played a part in the transport, but the extreme lack of sorting through thicknesses of tens of feet of fanglomerate and the large size of some of the boulders indicate rapid deposition from enormous mudflows or landslides. Some lubrication by water seems probable as the material came to rest on distinctly gentler slopes than did the glowing avalanches. The rare beds of sorted and fine-grained sediment are evidently made up of material reworked or stream-laid during intervals between successive slides. The irregular, westerly-facing declivities and kettles mark places where sediment was deposited against or on wasting Pleistocene ice. Had the level of this ice in Squamish Valley remained constant while the debris was being laid down there would be only a single fan, but continued lowering of the ice surface and retreat of its margins permitted construction of a series of terraces, each lower and extending

farther from the mouth of Cheekye Gorge than its predecessor.

Fluvioglacial deposits cover almost 3 square miles along the east side of Squamish Valley, from the terraced fans of Cheekye River to the head of Howe Sound. North of Mamquam River the upper surface of these deposits lies close to the 400 foot level, and in places their depth exceeds 300 feet. South of Mamquam River the deposits extend through a low rock-rimmed gap into the valley of Stawamus River and thence downstream for 3¼ miles to a low irregular westerly-facing scarp overlooking Howe Sound. Over much of this latter distance the fluvioglacial sediments are covered by Recent gravel laid down by Stawamus River, but on the westerly-facing scarp they are again exposed.

These fluvioglacial deposits vary from gravels in the northern part to fine sands, silts, and clays near Howe Sound. Pebbles of red and gray dacite, derived either from the terraces of Cheekye River or directly from Mount Garibaldi, make up a high proportion of the deposit at its northern end, but pebbles of other rocks, notably quartz diorite, are present in increasing amounts towards the south. Even near Howe Sound, however, particles of reddish dacite are locally sufficiently abundant to render silt distinctly pink. Stratification is well developed throughout the deposits. North of Mamquam River, clearly defined topset and foreset beds can be recognized. Near the mouth of Stawamus River the bedding in silt and clay is nearly flat-lying.

These fluvioglacial sediments were apparently laid down in part in a pro-glacial lake, in part along the stream draining the lake basin, and in part in marine waters at the mouth of the outlet stream. The topset and foreset bedding in the gravels north of Mamquam River show that the beds accumulated in a body of standing water whose surface lay slightly below the 400 foot level. The deposition of gravels in a relatively narrow belt along the east wall of Squamish Valley, instead of in a series of lobate deltas extending toward the center of the valley, indicates that westward drainage was impeded. Judging from the extension of these gravels southward from Mamquam River across the rock-rimmed gap, the altitude of which coincides very closely with the former water surface to the north, drainage must have been diverted into the Stawamus basin. Deposition under fluviatile conditions of

the gravels immediately southwest of this gap is demonstrated by the gentle and continuous southwesterly slope of the gravel surface. At this time the gap itself must have lain above sea level, as, presumably, did the surface of the body of water which had previously existed north of this gap. It is not known whether the sediments in the westerly-facing scarp near the mouth of Stawamus River were laid down under fluviatile or marine conditions, but clays at a similar altitude, 100 feet above present sea level, about a mile farther south contain marine fossils and were evidently laid down before late Pleistocene isostatic uplift of the coastal area was complete.

Dunes of volcanic dust on Brohm Ridge.—Dune-like ridges, up to about 15 feet high, resting on bedrock and till, are common in a limited area of the eastern part of Brohm Ridge (fig. 2). These ridges are composed entirely of homogeneous, unstratified, dust-size material, sufficiently coherent to be little if at all affected by wind or water, hence steep walls border the small stream channels cutting across them.

Mechanical analysis shows that less than 1 per cent of the material in the ridges exceeds 50 mesh (0.295 mm. diameter) and about 50 per cent exceeds 270 mesh (0.053 mm. diameter). This size distribution shows a fairly close correspondence to that of windblown dust of Kansas (Swineford and Frye, 1945) although the latter material is slightly finer. The distribution, form, texture, and homogeneity of these dune-like deposits conform with the idea of aeolian origin.

Under the microscope, the dust is seen to be composed of grains of plagioclase, green and brown hornblende, oxyhornblende, orthopyroxene, and glass containing fine microlites of feldspar. These crystal and lithic fragments are commonly angular and some display reentrant surfaces. Shards and pumiceous fragments are absent. The constituents clearly indicate a volcanic origin.

The source of this volcanic dust is fairly local, judging from its notably restricted distribution. Post-Pleistocene weathering of nearby lava is, however, almost imperceptible and is wholly inadequate to provide the volume of material in the dunes. More probable origins are either in wind erosion of the deposits of unconsolidated tuff-breccia farther west on Brohm Ridge and to the south, in Cheekye Basin, or in eruptions from Mount Garibaldi. Wind erosion of dry surfaces of the

tuff-breccias might produce detectable quantities of loess-like material of this composition, but such material should be fully as abundant on other slopes of Mount Garibaldi and particularly on any suitable gathering ground to the east, the leeward side during dry weather. The fact is, however, that no such dust deposits have been found elsewhere in the vicinity of the mountain. The observed concentration of dust on Brohm Ridge may, therefore, have resulted from one or two unusually heavily charged dust clouds or from a series of directed discharges of such clouds from Mount Garibaldi. If this hypothesis is correct the dunes may represent reworked deposits of hot volcanic clouds, the *nuées ardentes* themselves if this term be used in a restricted sense.

Time of the volcanic activity.—The eruptions of Mount Garibaldi can be dated in several ways. The presence of dacite in the terraced fans along Cheekye River and in the fluvioglacial deposits farther south clearly demonstrates that Mount Garibaldi already existed before the complete disappearance of the last Pleistocene ice sheet. The presence of a very few erratic boulders of quartz diorite on tuff-breccia at an altitude of 5,450 feet on the slope extending south from Diamond Head likewise testifies to an origin before the end of the Pleistocene epoch. The absence of erratics higher on the slope is significant, for at its Wisconsin climax the surface of the ice sheet probably attained an altitude of 6,400 feet in this locality. Fresh traces of the Cordilleran ice have been found up to 7,200 feet 10½ miles to the north, almost directly upstream, and to 5,500 feet 13 miles to the south, almost directly downstream. If the eruptions of Mount Garibaldi took place after the ice had passed its climax the absence of erratics at the highest levels would be readily explained.

Additional evidence on age is provided by a creek-side exposure at an altitude of about 4,250 feet on the south side of Cheekye Ridge 2½ miles southwest of Diamond Head. Here 3 feet of debris almost identical to the reddish tuff-breccias of Diamond Head, except that the largest blocks, only about 1 foot in diameter, are somewhat more rounded, rests with no sharp break on till lacking red dacite fragments. The gradational contact indicates that this red debris together with the underlying till was deposited by ice during a single

Fig. 4. The first appearance of the plug dome of Mount Garibaldi shortly after the Wisconsin climax of the Cordilleran ice sheet.

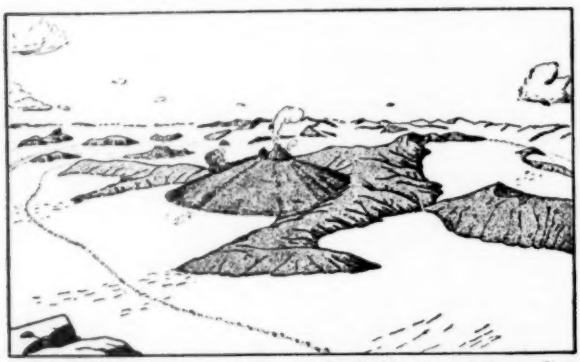

Fig. 5. The tuff-breccia cone of Mount Garibaldi at an intermediate stage in its growth.

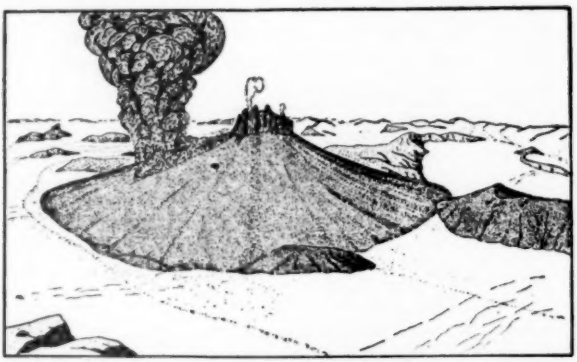

Fig. 6. The tuff-breccia cone of Mount Garibaldi at a late stage in its growth showing a glowing avalanche and accompanying hot dust cloud sweeping down its western flank.

Figs. 4-8 Reconstructed views of Mount Garibaldi during its growth and destruction as seen from an imaginary 8,800-foot peak about 5 miles to the southwest.

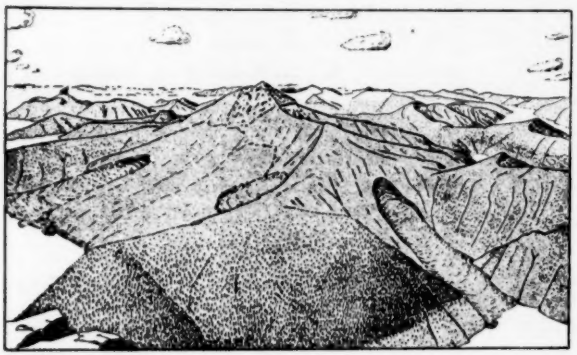

Fig. 7. Mount Garibaldi during the period of rapid deglaciation showing the partial collapse of the tuff-breccia cone as a result of melting of ice beneath its western and southern flanks.

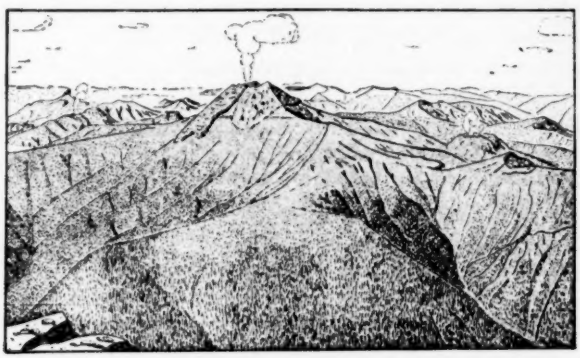

Fig. 8. The final volcanic activity of Mount Garibaldi, with lava flowing from the north vent. Deglaciation and collapse of the tuff-breccia cone was essentially complete at this stage. Other volcanic activity taking place in the vicinity at about this time was centered at Clinker Mountain (left middle distance) and Opal Cone (right middle distance).

period of glaciation. Inasmuch as the two-layered till sheet extends to the present surface and is weathered to a very shallow depth, it can be referred to the time of the Wisconsin ice sheet, the only sheet known to be represented in the glacial deposits of the Mount Garibaldi map-area. The material forming the dacite-free till was probably picked up by the ice prior to the eruptions of Mount Garibaldi; otherwise, a very radical divergence in the pattern of ice movement from the one recorded by striae would have to be postulated if ice were to reach this place without passing across some part of the area now covered by tuff-breccia. The evidence of this one exposure suggests, therefore, that Mount Garibaldi did not come into existence until some time after the early Wisconsin.

Volumes of volcanic rocks.—The volumes of the different rocks making up Mount Garibaldi can be fairly readily estimated for the surfaces on which they were deposited are sufficiently well exposed to permit their projection beneath the mountain. The combined volume of the tuff-breccias and the solid dacite core of the south peak is estimated to be about 0.8 cubic miles, and the volume of lava on the northern part of the mountain to be about 0.15 cubic miles.

The volume of detritus now reposing in the eastern part of Squamish Valley is more difficult to determine. If, however, the 10 square miles of this debris is assumed to have an average thickness of about 300 feet, a figure which seems to be within reason, its volume is about 0.6 cubic miles. A high proportion, though not all, of the sediment beneath these 10 square miles was derived from the western slope of Mount Garibaldi.

DISCUSSION

The southern part of Mount Garibaldi was of roughly conical form during and at the end of its Peléan activity. Presumably the cone was enlarged (figs. 5 and 6) by repeated avalanches of hot dacite dust and rubble that poured across its slopes from a rising mass of banded lava at the apex. In brief, Mount Garibaldi must have grown much like Mount Pelée. In one important respect, however, Mount Garibaldi is distinctly abnormal, for the present distribution and form of the tuff-breccias do not fit the simple picture of a cone

built on and burying an irregular topography. The tuff-breccias do not extend as far from their source down the pre-existing valleys of Cheekye River and Mashiter Creek as they do on the intervening ridge. Moreover, the destruction of the western slope of the cone is extreme whereas dissection of much of the southern slope is slight. Had a simple cone been eroded by streams, dissection would be expected to proceed at roughly uniform rates on all sides.

The gradational contact in the two-layered till sheet on the south slope of Cheekye Ridge indicates not merely that Mount Garibaldi grew during Wisconsin time, but that it was built while land at the 4,250 foot level was covered by ice. Hence, Cheekye Basin must have been filled to a similar level with ice, some of which would lie within 1½ miles of the vent (fig. 4). The cone, which in one place extends more than 3 miles from this vent, must certainly have been built onto the surface of the ice in Cheekye Basin (figs. 5 and 6). Accordingly Mount Garibaldi is to be classed as a "supra-glacial" volcano. Its unusual mode of origin accounts for anomalies already noted but hitherto unexplained.

What was the altitude of the surface of the ice sheet at the time of construction of the tuff-breccia cone? As already noted, land at and below the 4,250 foot level was buried by ice. Where the extreme alteration of schist at the tuff-breccia contact is observed the tuff-breccias were laid on bedrock before they became cold and chemically inert. Hence, the schist surface at and above the 4,500 foot contour in Cheekye Basin was either bare or covered by a layer of ice so thin that it was quickly melted by the hot debris. Parts of the cone built on bare rock would remain undisturbed when the ice sheet waned, and wherever the schist-tuff-breccia contact is found at or above the 4,500 foot level bedding in the overlying volcanic rocks is not disrupted. The ice surface on the south-western side of the volcano lay, therefore, in the vicinity of the 4,300 or 4,400 foot level, and was presumably at this or a slightly higher level elsewhere near Mount Garibaldi, except perhaps on the northern slope of Lava Peak which may have supported a local glacier (fig. 4).

By the time the tuff-breccia cone had reached its full height, its apex stood 9,000 feet above what is now sea-level, and approximately half as high above its pedestal of rock and ice

(fig. 6). At this stage the cone had roughly the same dimensions as the sub-aerial part of Mount Pelée. Where the cone rested on the ice occupying preexisting valleys or on ice-free ridges rising little or not at all above the general ice-level, the tuff-breccia extended approximately 3 miles from its source; where the cone was built against appreciably higher ground the lateral spread of the ejecta was correspondingly less. The total volume of the original tuff-breccia cone together with its dacite core was about 1.5 cubic miles; of this volume 0.8 cubic mile still remains. The volume missing from the western and southern parts of the supraglacial cone is about 0.7 cubic mile, a figure which agrees fairly well with the estimate of debris derived from Mount Garibaldi which now reposes in Squamish Valley. Only a relatively small amount of detritus from Mount Garibaldi seems to have been transported to the sea or to have been buried in Recent alluvium in Squamish Valley below the Cheekye fan.

A rise in the level of the ice sheet to the 5,500 foot level following the eruptions is indicated by rare erratics south of Diamond Head. Whether this was merely a recovery to pre-eruption levels after the thawing effects of the hot debris had waned, or a response to widespread climatic changes is not clear.

When the Cordilleran ice sheet later shrank, changes took place in those parts of the tuff-breccia cone which had been laid on the glacier. Where the layer of the ice between tuff-breccia and bedrock was thin, the slumps accompanying the wasting of the ice were only sufficient to produce minor breaks in the surface of the cone. In this way the scarp and trough topography of Cheekye Ridge may have originated. Where, however, the thickness of the ice was greater, as it must have been in Cheekye Basin, more radical changes took place (fig. 7). By the time all the ice melted from this basin the greatly oversteepened and broken flank of the cone was well prepared for the great slides which swept most of the debris into Squamish Valley.

After the tuff-breccia cone had been formed, lava issued from the north vent of Mount Garibaldi (fig. 8). The flow which extended westward was laid down on the landslide scar of the western face after the slumping of the tuff-breccia was partly complete; hence it must have been discharged at a late

stage in deglaciation or even after deglaciation was finished.

The history briefly told in the preceding paragraphs is recapitulated in the accompanying sketches. These portray the mountain at five stages in its growth and dismemberment, as it might have appeared from a vantage point on an imaginary peak 8,800 feet high and about 5 miles southwest of the cone. The cover of cloud, steam, smoke, and snow which must have masked the mountain during much of its growth has, for obvious reasons, been omitted. In other respects, however, they represent a sincere effort to depict, at several significant stages, the life history of this unusual volcano.

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University of British Columbia
Vancouver, British Columbia, Canada

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THE ENDOGENIC ENERGY OF THE EARTH

R. W. VAN BEMMELEN

ABSTRACT. Inquiry is made into the source and character of the earth's endogenic energy. Is it of a thermal or a chemical nature? The thermal conception debouches into a group of geophysical and geotectonic hypotheses in which convection currents play a leading role. The premise of convection currents is chemical homogeneity of the substratum. However, modern cosmochemical and geochemical considerations, as well as seismological observations, appear to be at variance with this premise. Therefore the hypotheses which take into account only thermal sources of endogenic energy cannot explain the manifold aspects of geological evolution. On the other hand, geological observations show that chemical processes are normally and systematically associated with tectonic processes (igneous activity, metamorphism of crustal rocks). It is suggested that the cosmic cooling of the earth, possibly a sudden cooling down due to the expulsion of the moon in its earlier stage of evolution, has thrown the earth's silicate mantle out of its chemical equilibrium. Restoration of the physicochemical balance in the earth's silicate mantle, especially in its outer part, effected by chain reactions and largely retarded by undercooling, is supposed to be the fundamental source of endogenic, terrestrial energy, since the cataclysms at the beginning of our planetary system.

INTRODUCTION

THE source of the endogenic forces stands as one of the most fundamental problems of geology. Since the origin of our planet, deformations and transformations have occurred in the outer part of the silicate mantle. These processes are still active in many regions, accompanied by such geophysical phenomena as earthquakes, and gravimetric and magnetic anomalies. Any consideration of the meaning and interdependence of the geological and geophysical phenomena involves some inquiry into the origin of the endogenic energy.

We can study only the effects of this energy. Geologists can say for certain that at least during about 2×10^9 years the processes of tectogenesis and volcanism have gone on without obvious decline in intensity. In still earlier times —from the origin of our planet, about 3.35×10^9 years ago, till the beginning of the geological era in a stricter sense —the earth may have been hotter, and the structural and volcanic revolutions in the outer crust may have been more intense (pyrospheric and anhydric stages of evolution); though we have no direct observations to support this possibility.

What is the nature of the terrestrial energy which kept the geological evolution going for such an immensely long time?

SOURCES OF ENERGY

The terrestrial energy is an inheritance from the protoplanetary state of evolution. After its separation from the sun (or its condensation from the protoplanetary gaseous disk with the sun in its centre), and the expulsion of the moon, no cosmic events interfered with the evolution of our planet.[1] Since its birth the earth should constantly have diminished its store of free energy by radiation, while a fraction of the internal energy has been used for tectonic and magmatic processes.

Energy can be stored and liberated in our globe in three ways: (1) by thermal vibrations of atoms, called "*internal heat*"; (2) by spontaneous splitting of nuclei of the *natural radioactive elements;* (3) by *inter-atomic physico-chemical forces.*

Besides these reserves of terrestrial energy there is the potential energy of the omnipresent gravity field of the earth, and the kinetic energy of the earth's rotation.

The geothermic gradient proves that the earth's interior is hotter than the surrounding space. Therefore the earth will cool down in the course of time if the loss of heat, by conduction to the surface and its ultimate radiation, is not counterbalanced by other sources of thermal energy. The classic theory of contraction accepts such a progressive cooling; however, this theory in its original and simple form of general contraction has lost its importance since the discovery of radioactive heat, the existence of enormous overthrusts, the recognition of tensional phenomena in the earth's crust (e.g. the African rift valleys), the existence of old glaciations, etc. Nevertheless, differential cooling down is

[1] Arnold Heim (1933) suggested that changes in speed of rotation other than secular retardation might have been of great importance for crustal deformations. The rotation of any celestial body that is not entirely solidified is influenced by another body that passes nearby, on account of the tidal effect. For instance, yearly encounter of a planet following more or less closely the earth's orbit would cause great and general disturbances of the crust. However, there are no geological or astronomical observations which support such a supposition for the geological part of the earth's history.

possible and might lead to major convection currents in the substratum; this is a geotectonic conception favored by many geologists.

The discovery of radioactive heat has opened the possibility that, instead of differential cooling, there might be a local heating. The energy produced by nuclear disintegration will have been considerable in the earlier stages of the terrestrial evolution; on the other hand, the natural radioactive elements of our days are only the bottlenecks, which release this kind of energy very slowly. Moreover, these elements seem to have concentrated in the outermost shell of the silicate mantle; otherwise the geothermic gradient would be much steeper.

There have been attempts recently to explain the endogenic phenomena by nuclear reactions with formation of new elements. But these hypotheses are not in harmony with our present scientific picture of the universe. Certainly all elements have been built up by nuclear reactions, but such processes no longer occur under the relatively low pressure and temperature conditions of the planetary phase of development (except the elements formed by disintegration of the natural radioactive elements).

However, if unequal heating by radioactivity is accepted as the basic source of endogenic activity, then also convection currents could ensue. This conception would debouch into the same complex of hypotheses as unequal cooling, mentioned above.

The third possibility, interatomic attractions and repulsions, is a powerful store and source of internal energy. Generally, these forces are locked in balanced physico-chemical systems, which hold their enormous potencies to potential rather than dynamic conditions. Once thrown out of static balance, however, the interatomic forces are capable of producing any effects of orogeny.

The fundamental condition for releasing this energy is the possibility of diffusion according to physico-chemical gradients (pressure, temperature, concentration, electric and magnetic field). If such diffusions in the solid state (either crystalline or amorphous) are possible with a speed entering into the range of geological periods and epochs, then important chain reactions will result.

The classic contraction theory appears to be an inadequate

explanation of the endogenic processes; it is not necessary to discuss its merits and shortcomings in this paper. Convection currents, however—due either to differential cooling, or to unequal heating—are nowadays the ruling theory. The premises of this conception are discussed in the next section. Thereafter a plea is made for the importance of physico-chemical reactions as a source of endogenic energy.

CONVECTION CURRENTS

Convection currents in the earth's silicate mantle are presumed to be the result of reversible changes of density, due to unequal cooling or heating. Thus they are conceived as a simply thermal process.

A fundamental condition for major convection currents is the chemical homogeneity of the substratum. Vening Meinesz (1934, p. 55) stated explicitly: "If no homogeneous layer would exist below the crust, i.e. if the density would gradually increase downward, no convection would be possible." We will first discuss the validity of this premise of convection currents.

Given the mean density of the earth (5.527 g/cm^3), the moment of inertia of our planet (8.07×10^{44} g/sec^2), its mean radius (6.371×10^8 cm), and the approximate depth of the seismic boundary between the silicate mantle and the core (2.9×10^8 cm), there is only a limited choice of density distributions. According to Haalck, density may have values between 4 and 5 at 1200 km, the depth of a problematic seismic discontinuity, and between 5 and 9 at a depth of 2900 km, the base of the silicate mantle. If the silicate mantle were homogeneous, then the increase with depth from 3.4 to 5-9 would be exclusively the result of increasing pressure. The latter attains a value of about $1\frac{1}{2} \times 10^6$ atm. at the base of the silicate mantle. On the other hand, rising temperature would have a counter-effect, tending to decrease the density with increasing depth.

It is not *a priori* impossible that the increase of pressure, even when counteracted by rising temperature, might cause the specific density of silicate matter to become twice or thrice as great as its density under surface conditions. However, such important increases of density can not be determined by our laboratory experiments; neither have they been predicted by thermodynamic extrapolations of the latter. Evidently, this

premise of chemical homogeneity is a debatable, dubious assumption; it needs further support from other branches of science before it can be accepted as a probable basis for geophysical deductions. Recent meteorite studies by Brown and Patterson, and geochemical studies by Barth, Ramberg, and others, are of importance in this connection.

Brown and Patterson (1948) have studied the composition of silicate meteorites on a more quantitative basis than has been attempted hitherto. These authors demonstrated that: "... if one assumes that the observed distributions of elements represent equilibrium distributions, then equilibrium must have been established at temperatures of the order of 3000°C and pressures of the order of 10^5—10^6 atm. Similarly, it is demonstrated that the conditions at which equilibrium was achieved varied from meteorite to meteorite in such a way that the greater the metalphase content, the greater the temperature and/or pressure. The data indicate strongly that meteorites had their origin in a planet similar to the earth in general physico-chemical characteristics."

Bauer (1947), revising data given by Paneth, estimates the age of the meteorites at 3.4×10^9 years (by means of the helium method); this is in close agreement with the age of the earth, estimated by Holmes (1947) at 3.35×10^9 years (by means of the lead-isotope method). Therefore, the meteorites were probably formed during the initial stage of the origin of our solar system. Kuiper (1951) suggests that they resulted from the destruction by collision of some planetary masses which occupied the orbit of the planetoids between Mars and Jupiter. The ideas of Hoyle and Lyttleton lead to a similar conception about the origin of meteorites.

Thus, if the composition of the meteorites represents in a certain degree physico-chemical equilibrium conditions in the parental planets, these equilibria must have been attained shortly after their origin. The physico-chemical conditions in these parental planets being comparable with those of our globe, the same conclusion will hold good for the earth's silicate mantle; also in the latter there must be a downward shift of the chemical composition due to the existing gradients of pressure and temperature. The graphs of the changes in chemical composition of stony meteorites, set up by Brown and Patterson on the basis of the varying content of metal phase

(1948, figs. 7 and 8), link on (by extrapolation) to the values for the mean composition of plateau basalts and the mean for all igneous rocks. This is another argument in support of the assumption that these graphs can be compared, to some degree, with the chemical composition of the earth's silicate mantle in greater depths. Thus we see that the recent meteorite studies of Brown and Patterson support the conception that the downward increase of density is at least partly the result of changes in the chemical composition, and this is at variance with the premise of convection currents.

This inference has been corroborated by recent studies of Ramberg (1948) and Barth (1948). The latter pointed out that there is a regular downward decrease of the volume occupied by oxygen. This decrease ranges from 96.87% in the oceans (hydrosphere), 92.12% in the granitic "ichor," 91.83% in the average igneous rocks, and 91.11% in average plateau basalts, to 90.00% in the olivine of the peridotite layer. Barth concludes that "this decrease of the oxygen volume with depth represents an approximation to the thermodynamic equilibrium. When highly oxidized surface rocks are brought down to great depth, oxygen will be squeezed out of the mineral lattices and returned to the surface. Therefore, the deeper parts of our globe cannot become oxidized."

Apparently the chemical composition of the outer part of the earth's silicate mantle, called the tectonosphere, changes with depth according to thermodynamic equilibrium. It is quite probable that such more or less gradual shifts in composition do occur also in its deeper parts. Therefore modern cosmochemistry and geochemistry are not in agreement with the premise of convection currents, viz. chemical homogeneity of the substratum.

There is another serious objection against convection currents in the substratum, based on seismological evidence. The seismic Mohorovičić-discontinuity at a depth of about 40 km. is presumed to represent the base of the crystalline crust. Below this discontinuity convection currents are supposed to occur in the substratum, exerting a viscous drag on the overlying crust. In other words, the silicates above this seismic boundary should be in a crystalline state and those below it in an amorphous state. However, at this boundary the velocity of the longitudinal seismic waves increases with a sudden jump

from 6.5—7 km./sec. to 8.1—8.2 km./sec. Where these rapid increments of speed take place, there is evidently a change from a less rigid and more compressible rock on top, to a more rigid and less compressible rock under it. Converging evidence (laboratory experiments on the elastic properties of rocks, density distribution in the tectonosphere, chemical compositions, and petrological considerations) makes it probable that the matter overlying this discontinuity is an amorphous silicate melt of basaltic (gabbroic) composition, and below it the state is crystalline and the composition ultra-basic (peridotitic). This generally accepted interpretation is just the reverse of the picture given by adherents to the hypothesis of convection currents, as stated above.

There is yet another difficulty, based on seismological evidence. Gutenberg (1950 and in earlier papers) points out that at a depth of about 80 km. the velocity of the seismic waves decreases slightly, and it begins to increase again at a depth of about 150 km. The most obvious interpretation of this decrease is that between 80 and 150 km. depth the crystalline peridotite layer passes downward into the molten (i.e. amorphous) matter of the substratum ("sifema"). This decrease is also at variance with the conception of convection currents, because the stirring effect of these currents should have wiped out all irregularities, homogenizing the substratum in chemical as well as physical respect.

Thus neither geochemical nor seismological considerations support the premise of convection currents. Yet these objections are of an indirect nature, being based on deductions and extrapolations. Are there geological observations more directly in favor of such major currents of matter in depth?

Differential vertical movements, continuing in the same sense for dozens, even some hundreds of millions of years, form an essential aspect of geological evolution. In the Bulletin of the American Association of Petroleum Geologists (vol. 35, no. 2, 1951), a most valuable symposium of the possible future petroleum provinces of North America, many sections deal with the general trend of rising regions and adjacent subsiding basins; for instance, the rise of the Appalachian region and the subsidence of the Gulf of Mexico. Rise and subsidence might be enlarged about ten times by isostatic control. Matter with a mean specific density of 2.75 is removed

by erosion from the rising area, and it is partly deposited as sediments with a mean specific density of 2.50 in the adjoining subsiding trough. But isostasy can not be the ultimate cause, for the rising column grows heavier than the subsiding one. Internal forces keep the process going.

What is the cause of these differential vertical movements of consistent trend during long geological periods? It may be the action of convection currents in the substratum, with upward moving columns under the rising areas and downward moving columns under the subsiding areas. The upward moving column of a convection current should be the hotter one, in which thermal expansion has caused a decrease of specific density; whereas the downward moving column should be cooler with a higher specific density due to thermal contraction.

However, there are some serious objections to such a conception, related to the energy needed to keep them going. As stated this should be either differential heating by radioactivity, or differential cooling by conduction of heat through the crust and its ultimate radiation into space.

In the case of differential heating, this could not be the result of an unequal distribution of radioactive elements in the substratum, viz. the rising columns being more radioactive than the subsiding ones. For convection currents, intermittently or continuously active during immensely long periods, should have stirred the substratum to complete chemical homogeneity.

The substratum being homogeneous, it might be supposed that the overlying crust contains more radioactive energy-spenders above the rising columns than above the subsiding ones. But then, in the course of time, erosion and sedimentation should have restored this unequal distribution, removing the radioactive elements from the rising area and depositing it in the adjacent subsiding basin.

In the case of differential cooling, the question arises why cooling should be persistently stronger under a subsiding block, notwithstanding the fact that it is covered by ever thicker piles of sediments; whereas it should keep continuously a lower value in a rising tract of land, where the crystalline crust becomes gradually thinner by erosion, and where in many instances external volcanism considerably aids the transfer of heat to the surface.

It appears from the foregoing considerations that convec-

tion currents—either by differential heating or by differential cooling—do not satisfactorily explain the continuous rise or subsidence, exhibited by crustal blocks during long geologic epochs. We have to look for other, slow but persistent processes in the earth's silicate mantle. Can it be that these are not of a thermal, but of a chemical nature? This possibility is now considered.

PHYSICO-CHEMICAL CHAIN REACTIONS

Gravity is a dominant and persistent force which cannot be set aside. Deviations from gravitational equilibrium create stress fields and, when certain limits of strain are surpassed, displacements of masses and tectonic deformations ensue. So we have to investigate how such deviations from gravitational equilibrium can originate.

There are two possibilities: either the distribution of matter remains constant, but the gravity field changes by cosmic forces, or there are changes in the distribution of matter, which cause deviations from gravitational equilibrium.

The first possibility is the starting point of geophysical hypotheses based on changes in the velocity of rotation and the orbit of the earth, tidal movements, shifting poles of the axis of rotation, and the like. These primary causes of deformations may have been important for the older, more turbulent stages of the earth's evolution, for instance in relation to the expulsion of the moon, but not for the geological era in a stricter sense, to which Lyell's doctrine of uniformitarianism can be applied.

For the geological evolution *sensu stricto*, at least for the tectonic movements of the present, we have to assume that the gravity field of the earth is constant, and that changes in the distribution of matter cause deviations from gravitational balance. Moreover, it is clear that the present geotectonic relief, with continental and orogenic highs and oceanic lows, does not represent gravitational equilibrium.

So we restrict our problem to the question: How do deviations from gravitational balance originate? This occurs when the specific density of matter in definite geometric positions alters. It is immaterial for the geotectonic effect whether such changes of specific density are reversible or irreversible in a thermodynamic sense. They might be the result of reversible

expansions and contractions of matter due to changes of temperature and pressure, as assumed in the thermal geotectonic hypotheses. However, the changes of specific density could also be irreversible, having a more permanent, chemical character.

Do we know geological processes that are accompanied by such chemical changes of density? Indeed, the formation of igneous rocks and regional metamorphism are geochemical processes accompanied by changes of density. Studies of regional geology have shown that there is an intimate and systematic relation between tectonic and igneous processes, such as the rising and sinking of the migmatite front (Wegmann, 1935), the emplacement of plutonic bodies (H. and E. Cloos), the association of certain petrographic provinces with definite stages of orogenic evolution (van Bemmelen, 1950a). Therefore we are assured that the chemical and physical properties of crustal matter do vary in the course of the geological evolution. The history of our planet, according to the inductive arrangements of basic facts, appears to be a long and complicated story of deformations and transformations of the earth's crust by physico-chemical chain reactions.

These chain reactions occur in accordance with the second main law of thermodynamics; they have a definite trend and they are irreversible. The author (1949b, p. 732) suggested the following general course of the process: 'The cosmic process of cooling of the earth causes a flow of energy from the inner, hotter parts of our planet to the surface. However, this is not a simple thermal process. On its way to the surface, before the ultimate radiation and dissipation into space, free energy assumes all kinds of conditions. In the first place, the temperature gradient initiates exothermal chain reactions with a disperse, atomic and ionic flow of matter, bringing about geochemical adjustments in the composition of the earth's shells. Such physico-chemical processes cause changes of density, and, as they are unevenly distributed, they result in disturbances of the hydrostatic equilibrium. Therefore, the equilibrium-disturbing effect of the physico-chemical process periodically gives rise to restorative reactions which have the character of more concentrated mass displacements. These equilibrium-restoring movements in depth cause differential vertical movements of the earth's crust, called primary tectogenesis.

'These differential vertical movements of the earth's surface disturb in their turn the gravitational balance in the outer crust and the sedimental epidermis. The ensuing equilibrium-restoring reactions belong to the class of secondary or gravitational tectogenesis.'

Thus we see that the chemical conception regarding the origin of the endogenic energy of the earth leads to a *bicausal interpretation of the crustal deformations*. The main features of the earth's relief, such as mountain ranges and geosynclines, plateaus and basins, are the effect of differential vertical movements (*primary tectogenesis*), whereas the folding and thrusting movements of the rock-strata into depressed areas is the counterpart of dilatation and removal by sliding of matter from the adjacent more elevated parts of the crust (*secondary tectogenesis*).

It is not necessary, according to this line of thought, to accept some hypothetical tangential compressive force in the crust, which creates the larger features of relief. Dispersive and/or concentrated transport of matter beneath and in the crust, due to thermo-dynamic as well as physico-chemical gradients, might be able to account for the upward and downward movements of the earth's surface. On the other hand, the ubiquitous force of gravity could be held responsible for the ensuing folding and thrusting due to sliding movements; alpine geologists in Switzerland and France—Lugeon, Gignoux and others—are convinced of the importance of this principle of "écoulement par gravité."

Moreover, the author showed in his synthesis of the geological evolution of Indonesia, a region covering about four per cent of the earth's surface, that the bicausality concept provides a harmonious picture of the interaction and interdependence of the observed tectonic, magmatic, and geophysical phenomena in that archipelago. The rules governing orogenic evolution, derived by inductive marshalling of the basic geological facts of that area, may be of more than local importance.

One point needs closer consideration, namely the time of the cosmic cooling, which started these complicated physico-chemical chain reactions. For it is not necessary that the reactions follow immediately after the cooling down. There may be a considerable time-lag, an intervening static condition like

that of under-cooled glass with potential physico-chemical energy.

Calculations regarding the heat balance of the earth's crust show that at present there may be a balance between the generation of radioactive heat and the heat flow to the surface (Nawijn, 1950). Consequently, there could be hardly any cooling down of the earth in these days, whereas the endogenic forces are yet very active, for instance in Indonesia and in the Caribbean area.

However, the cooling down which has thrown the earth's silicate mantle out of its physico-chemical balance, might have taken place at the very beginning of the geological evolution. If during the turbulent period of the formation of a solid planet from a proto-planetary gas-sphere some catastrophe happened, which caused a sudden loss of thermal (free) energy, so that the outer part of the earth's silicate mantle became undercooled, then it is conceivable that the physico-chemical chain reactions were more or less retarded and even completely halted due to the increase in viscosity. The process of "devitrification" of this glassy mantle might have been slowed down to such an extent that it is not yet completed in the present time, billions of years later.

Indeed, such a sudden loss of free thermal energy probably did occur in the pyrospheric stage of the terrestrial evolution, when a part of the silicate mantle was expelled by a jet of evaporated silicates and oxides (van Bemmelen, 1948 and 1949a). Outside the limit of Roche this expelled part of the silicate mantle assumed a spherical form by its own gravity field, and initially our newborn satellite showed archaeo-volcanic activity, like the earth's surface at that stage of evolution. However, quick cooling down brought the lunar volcanism to a stop, and in our day the frozen face of the moon still shows the traces of its paroxysmal birth. Most probably physico-chemical gradients, representing potential energy, are still present in the moon; however, they are not strong enough to overcome the viscosity of the moon's silicates and to start chain reactions.

In the earth, on the contrary, due to its larger volume, and perhaps aided by entrapped solar gases (hydrogen), a slow process of physico-chemical adjustments started in some places. This process of the restoration of physico-chemical

balance has been called "hypo-differentiation" by the author (1948). It is a delayed process like devitrification of glass, and it starts by atomic and ionic diffusions in depth. Moreover, being a reaction to cooling, it is an exothermal process; accordingly if once started, it has the tendency to continue and reinforce itself. It is an incessant battle between the generation of heat by exothermic processes on the one side, and the loss of heat by conduction and volcanism on the other. Therefore the ensuing tectonic processes get the physical character of relaxation pulsations, caused by intermittent loading and unloading (van Bemmelen, 1952). Meanwhile, the overlying crust is deformed and transformed by these physico-chemical chain reactions, which can be considered as the true source of the endogenic energy of the earth.

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Geol. Inst. of the State University
Utrecht, Netherlands

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SEDIMENTATION AND STRATIGRAPHY OF THE HURONIAN OF UPPER MICHIGAN

S. A. TYLER and W. H. TWENHOFEL

PART 2

Siamo Formation

Distribution.—The Siamo formation forms a continuous belt along the northern flank of the Marquette district. This belt widens east and south of Negaunee where it swings south across the axis of the Marquette syncline. West of Palmer and a short distance east of the New Volunteer Mine the Siamo thins rapidly and passes laterally into the Ajibic quartzite. Farther westward on the southern flank of the syncline the Siamo loses identity as a formation. It is obvious that some parts of the Siamo have time equivalence with some parts of the Ajibic.

Many students of the Lake Superior Precambrian have correlated outcrops and formations on the basis of rock type and lithic sequence. This has led to error in the Palmer area where the iron formation and the overlying quartzite have long been regarded on the basis of rock type and lithic sequence as equivalents of the Negaunee iron formation and the Goodrich quartzite respectively to the north and west. The present studies indicate that the quartzite is a part of the Siamo and the iron formation is the Goose Lake member of the Siamo. Figure 4 shows the general geology of the Palmer area as outlined by Van Hise and Leith (1911, plate 17) and figure 5 shows the recent revisions of the geology of this area based on detailed field mapping and magnetic survey by Eiler Hendrickson and field studies by S. A. Tyler. The Goose Lake iron-bearing member of the Siamo formation forms a continuous belt extending from the vicinity of Goose Lake southeast to the old Palmer Mine. A short distance west of this mine the iron formation becomes interbedded with quartzite and disappears westward. The continuity of this belt of iron formation indicates that the west end of the supposed Palmer fault as shown in figure 4 is either non-existent or of minor importance. The Volunteer fault trends northeast from the

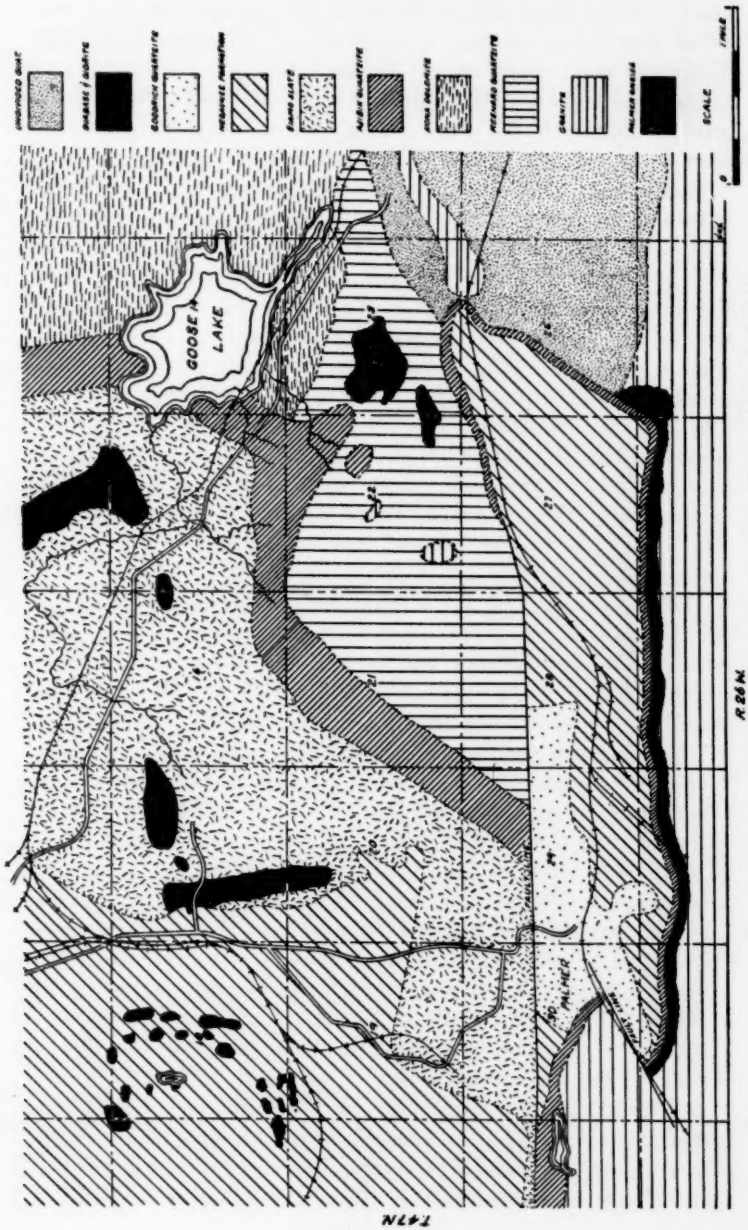

Fig. 4. Geology of the Palmer area after Van Hise and Leith (1911).

old Volunteer Mine and produces the displacement farther east which heretofore has been attributed to the Palmer fault. The Volunteer fault dropped the Goose Lake iron formation and overlying Siamo quartzite downward to the south; the Palmer mining district is the result. The type locality of the Siamo formation is in the Siamo Hills southeast of Teal Lake.

Lithology.—Although the Siamo formation is generally known as the Siamo slate, there is little merit in the lithic term as the lithology is complex and the sequence is variable. The rock types include laminated gray, black, red and green argillites; dark gray or greenish-gray fine- to medium-grained argillaceous quartzites (commonly known in the Lake Superior region as graywacke); clean white quartzites; fine to coarse conglomerates; and an evenly bedded iron formation member. The lithic sequence southeast of Negaunee from the base upward consists of thin-bedded argillite, argillaceous quartzite grading upward into clean white quartzite, and locally at the top of the formation a green, red, or black argillite. Current ripple mark, cross-lamination, and cut-and-fill structure are characteristic. Beds are lenticular and gradation from quartzite into a coarse granule of gravel conglomerate is common. Many beds of quartzite contain vein quartz pebbles. The transitional zone between the quartzite member of the Siamo and the Negaunee formation at the Maitland Mine contains lenses of well-rounded white quartz pebbles. The upper part of the quartzite member of the Siamo south of the Empire Mine also contains well-rounded white quartz pebbles and occasionally poorly rounded boulders of granite to a foot in diameter. The quartzite member of the Siamo south of the Volunteer Fault (previously designated Goodrich) is locally conglomeratic. There are magnificent exposures of coarse conglomerate at the Isabella Mine where the materials are poorly sorted and consist of angular blocks of iron formation up to three feet long and one foot wide, pebbles and boulders of white vein quartz to 18 inches in diameter, and quartzite boulders to 8 inches in diameter. These seem to occupy a channel in the iron formation.

Northwest of the Volunteer fault the Goose Lake iron formation member has a somewhat varied mineral composition. Adjacent to some of the larger basic intrusives the formation consists of stilpnomelane, siderite, magnetite, and chert,

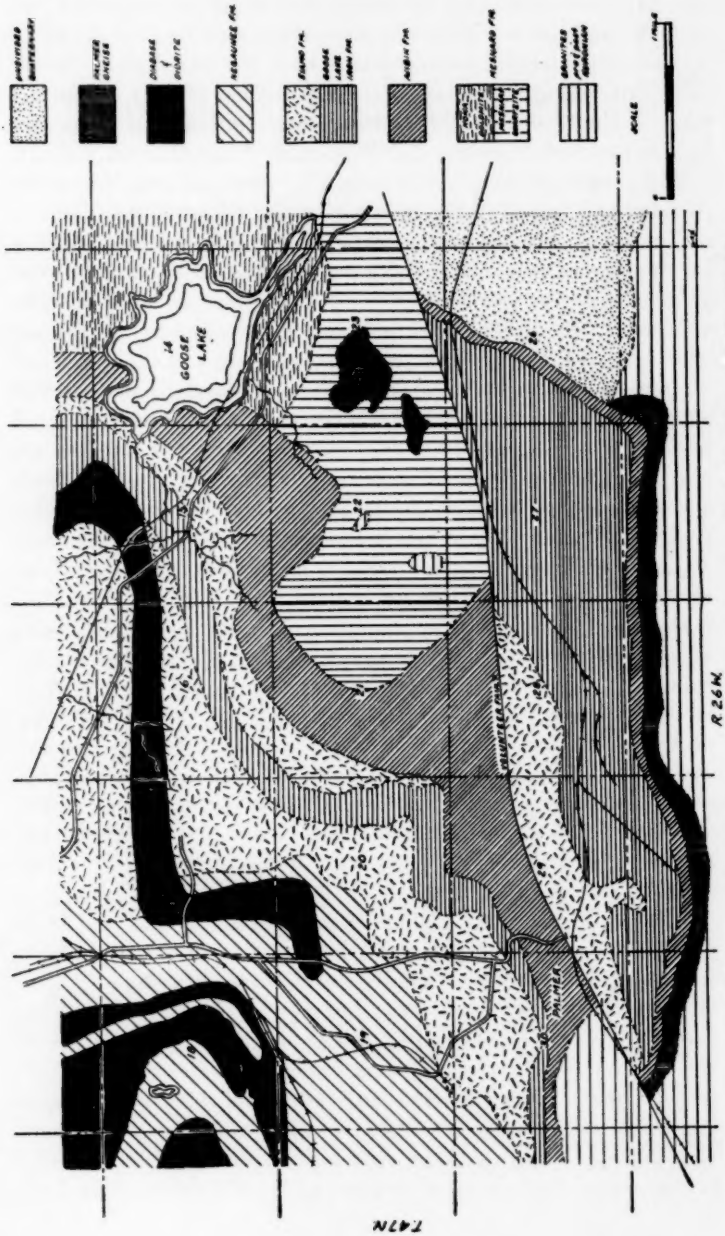

Fig. 5. Geology of the Palmer area as revised by Tyler and Twenhofel.

but in areas free from intrusives the dominant minerals are siderite and chert. The iron formation has been oxidized to a ferruginous chert in the vicinity of the old Palmer Mine. It is interesting that Van Hise and Bayley (1897) mapped a part of the Goose Lake iron formation southeast of Negaunee but correlated it with the Negaunee. Van Hise and Leith (1911) omitted this area from the map of the Marquette district and included the rocks with the Siamo formation.

There are excellent exposures of the Goose Lake member of the Siamo formation south of the Volunteer fault in the Palmer district, particularly in the long ridge south of the village of Palmer. The rock is composed of alternating laminae of bright red jasper and gray specular hematite. Seventy-six laminae of jasper and hematite were counted in a thickness of 36 inches. At the old Platt Mine 110 laminae were counted in 10 inches at one place and 54 in 3.5 inches at another place. Numerous beds of medium- to coarse-grained reddish quartzite interbedded with the jasper and hematite are also present on the ridge south of Palmer. The quartzite beds range in thickness from a fraction of an inch to zones of an observed maximum of 11 feet.

Coarse clastics including conglomerates in the form of lenses are interbedded with the Goose Lake iron formation at the falls on Cascade Brook south of Palmer, at the Old and New Richmond Mines, and at the Moore Mine. At the west end of the old Richmond open pit there is a lens of conglomerate about 6 feet thick interbedded with the iron formation. This consists of well-rounded cobbles of white quartz in a matrix of coarse angular sand and chlorite. This lens of conglomerate can be traced through the open pit for a distance of several hundred feet parallel to the strike of the beds.

At the Moore Mine a short distance east of the old Richmond Mine an extensive area of the Goose Lake iron formation has been stripped for mining and then abandoned. This stripped area provides one of the best and most interesting exposures of the Goose Lake member of the Siamo anywhere in the Marquette district. A zone about 100 feet thick is exposed which contains numerous beds and lenses of coarse quartzite and conglomerate interbedded with the iron formation. Many clastic zones extend only a short distance parallel to the strike, but one zone extends at least 500 feet. The beds

and lenses range in thickness from a fraction of an inch to about 15 feet. Some lenses consist dominantly of coarse quartzite with an occasional white quartz pebble. Others are argillaceous quartzite which has been altered to mica schist, and still others consist of coarse conglomerate composed of well-rounded pebbles and cobbles of white vein quartz, chert, white quartzite, granite, and a gray schistose rock. Most range from 1 to 3 inches in diameter, but a boulder with diameter of 8 inches was seen (fig. 6). Occasional single boulders 6 to 8 inches in diameter composed of fine-grained siltstone or white vein quartz are present in chert beds which otherwise are free of clastics. Bases of the quartzite and conglomerate beds and lenses are usually conformable with the associated beds. However, two equi-dimensional bodies of quartzite (3 feet wide parallel to the bedding by 3 feet perpendicular to the bedding) were seen in the iron formation. These seem to be filled channels that were cut in the iron formation (fig. 7).

In the eastern exit of the New Richmond open pit mine a rock cut exposes a conglomerate some 20 feet thick which overlies oxidized cherty iron formation. About 30 feet of interbedded oxidized cherty iron formation and reddish quartzite overlies the conglomerate. The materials of the conglomerate are poorly sorted and consist of well-rounded pebbles, cobbles, and boulders of white vein quartz and fresh granite with salmon pink feldspar in a matrix composed of pink feldspar and quartz sand.

Pyroclastics are also present in the Goose Lake iron formations in the Palmer area. A rock hill rising out of a swamp in the NW 1/4 of the SW 1/4 of Section 28, T. 47 N.,

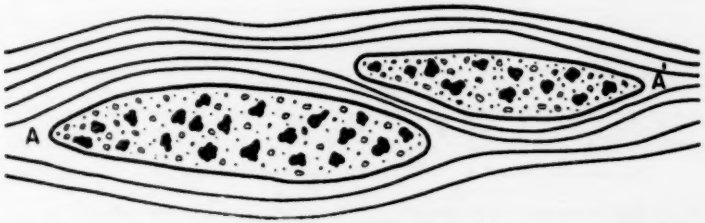

Fig. 6. Diagram of two lenses of conglomerate in the Goose Lake iron formation at the Moore Mine. Boulders are up to 8 inches in diameter and most consist of fine-grained quartzite, red granite, and vein quartz. The combined length (A-A') is between 40 and 45 feet. The thickness of each lens ranges to about 3 feet.

R. 26 W. has excellent exposures of a somewhat sheared volcanic tuff and agglomerate. Angular to well-rounded pebbles and cobbles of acid to basic volcanic materials are imbedded in a fine-grained greenish tuffaceous matrix. The center from which this material was ejected is unknown. The amygdaloidal flows west of Palmer assigned to the Ajibic by Van Hise and Bayley (1897, p. 312) may also be of Siamo age.

Thickness and stratigraphic equivalents.—Van Hise and Leith (1911, p. 262) estimated the thickness of the Siamo formation as between 600 and 1300 feet. It is obvious that the thickness varies from place to place. The formation is either very thin or absent on the southern limb of the Marquette syncline.

The Palms formation of the Penokee-Gogebic district and the Footwall slates of the Iron River-Crystal Falls district (according to Pettijohn, 1946) roughly occupy the same position in the Huronian sequence as the Siamo formation. The Palms formation has a maximum thickness of about 800 feet in the area east of Sunday Lake, and normally ranges in thickness from 400 to 500 feet over the rest of the district. The Palms may be subdivided into three members: (1) a basal conglomerate, (2) a laminated siliceous argillite and very fine-grained quartzite, and (3) an upper vitreous quartzite.

The basal conglomerate is usually less than 5 feet thick and is composed of pebbles and cobbles of white vein quartz, chert, granite, and green schist in a sandy matrix. At the top is a thin zone of quartzite with excellent cross-lamination.

The middle member forms most of the formation and consists of alternating laminae of siliceous argillite and fine-

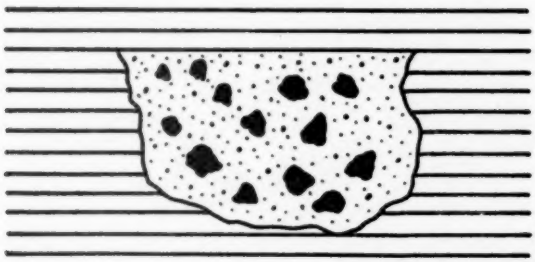

Fig. 7. Diagram of clastics filling what seems to be a channel cut in the Goose Lake iron formation at the Moore Mine. Width of this channel is between 2 and 3 feet.

grained quartzite. Laminae appear very even, but close examination shows many minor irregularities in the form of small ripple marks, and cross-lamination is present in some of the thin layers of fine-grained quartzite. The character of the lithology and laminations is shown by the following descending section which is exposed on the high hills east of Wakefield.

	Inches
Quartzite, fine-grained. In a lateral distance of 12 inches	0-1/2
Siltstone	1/32
Quartzite, fine-grained	1/4-3/4
Siltstone	1/4-5/8
Siltstone. In a lateral distance of 10 inches	0-1/2
Siltstone, dark brown	1/32
Siltstone, in a lateral distance of 8 inches	1/8-1/2
Siltstone, dark brown	1/32
Silststone	1/8-3/8
Quartzite, fine-grained	3/8
Siltstone, dark brown	1/16
Siltstone, light brown	1/16
Quartzite at base, siltstone at top	1/16-3/8
Siltstone	1/4-1/2
Quartzite	0-1/4
Siltstone, fine-grained	1/4
Quartzite	1/4-3/8
Shale	1/32
Quartzite with siltstone at top. In a lateral distance of 16 inches	0-1
Dark shale	1/32
Quartzite, cross-laminated with vertical component of 1 inch and horizontal component of 4 inches. In a lateral distance of 8 inches	0-2
Siltstone	3/8-3/4
Quartzite, reddish, fine-grained	1/8-1/2

The thickness is a couple of hundred feet in the Wakefield exposure. It is difficult to understand the presence of excellent lamination coupled with the type of sediment and the extensive area over which this type of sediment extends.

The upper vitreous quartzite member, about 50 feet thick, is composed of fine- to medium-grained, angular quartz grains. Bedding is irregular, and current ripple marks and cross-lamination are extensively developed.

Environment of deposition.—The argillaceous character of the quartzites of the Siamo indicates poor sorting and probably rapid deposition of the sediments. The alternating argillite and quartzite beds suggest fluctuating conditions over the sites of deposition. The current ripple marks, extensive cross-

laminations, and cut-and-fill expressed in sandy beds indicate waters with relatively strong currents at times. The presence of pebbles, cobbles and boulders which are present individually or as lenses indicates shallow waters with currents of competency adequate to transport such materials. These features very strongly indicate that the sediments were deposited in a delta environment. The abundance of coarse clastics and the rapid thinning of the formation from east to west on the southern flank of the district suggest that the streams were entering the site of deposition from the east or southeast.

The Goose Lake iron-bearing member of the Siamo is a thinly and evenly laminated cherty iron formation that lies within and is surrounded by argillaceous and sandy sediments. The accumulation of the composing sediments requires deposition on bottoms that in some way were protected against general entrance of muds and sands. However, the numerous beds and lenses of quartzite and conglomerate and the gradation laterally of the iron formation into quartzite as shown in the Palmer area show that conditions at times were such that currents could bring coarse clastics to parts of the area where the iron formation was being deposited. The general absence of cut-and-fill below the quartzite and conglomerate lenses suggests that the ferruginous cherts were sufficiently rigid shortly after deposition to resist the erosive power of rather strong currents. Furthermore, the individual cobbles and boulders at the base of the conglomerate lenses do not penetrate nor depress the underlying chert laminae. This seems to indicate that the siliceous deposits had assumed a high degree of rigidity shortly after deposition. It is interesting to note in this connection that Irving (1886, p. 256) long ago recognized that the iron formation became indurated at an early date for he states "that any satisfactory explanation must provide for the fact that these materials reached their present indurated and silicified condition, in some cases at least, before the production of the next overlying layer of the series." The presence of cut-and-fill which was observed in a few cases indicates conditions that permitted erosion of the recently deposited ferruginous chert. The jasper pebbles, cobbles, and boulders in the conglomerates exposed at the old Volunteer Mine, at the Isabella Mine, and on the northern side of the jasper hill south of the Village of Palmer

show that the iron formation was sufficiently consolidated to produce coarse clastics at the time these clastics were formed. The coarse conglomerates at the Isabella Mine flanked by even-bedded jaspers to the east and west suggest that these deposits formed at the mouth of or in a stream where currents were strong.

The general plan of the Goose Lake member of the Siamo suggests that these deposits were made in a deltaic lake; the deposits are underlain, overlain, and surrounded by deposits which seem best explained as of deltaic origin.

The environment of deposition of the Palms formation of the Penokee-Gogebic district is somewhat difficult to understand. Even lamination with lensing on a small scale, the small ripple marks, and the minute cross-lamination of the interbedded fine-grained sands and siliceous silts show that currents were of low competency. Slow deposition seems indicated. The authors envision a broad, shallow, subsidence basin over which currents were weak because of shallowness of water. This basin probably was connected with a deeper one in which other types of sediments were deposited. At one place on the hill east of Wakefield 130 laminations of fine sand and silt were counted in 3 feet and 5 inches of thickness. If high tides were responsible for the deposition, a minimum of two months would have been required to deposit this thickness of sediment. Perhaps the laminations were deposited only at times of spring tides in which case about 11 years would have been required to deposit the 130 laminae. Speculation of the rate of deposition is interesting, but with existing data no solution of the problem is possible. It must be assumed that the area of deposition was subsiding to account for the considerable thickness of the fine sand and siliceous silt member of the Palms.

The coarseness of grain, the thicker units, irregular bedding, large current ripple marks, and cross-lamination in the upper quartzite member of the Palms formation show a change of environment from that prevailing during the deposition of the middle member. Perhaps larger supplies of sediments became available through uplift or increased rainfall on the land areas that provided the sediments, or the area of deposition may have subsided sufficiently so that strong currents could enter and introduce coarse sands.

Negaunee Formation

Distribution.—The Negaunee iron-bearing formation is present as an almost continuous belt along both the northern and southern flanks of the Marquette syncline. There are local areas, such as a 5-mile zone east of Lake Michigamme on the north side, a short interval on the south side south of Clarksburgh, and a 5-mile zone extending from about one mile west of the Champion Mine to the Chippawa Mine in the Republic trough where the formation is either thin or absent. The most extensive surface area underlain by the formation is in the Ishpeming-Negaunee area where it swings southward across the axis of the syncline and is repeatedly brought to the surface by east-west trending faults. The type locality is in the City of Negaunee and the area immediately to the south. Exposures are excellent.

Lithology.—The iron-bearing formation has three facies:—(1) siderite and chert with subordinate iron silicate and iron oxides, (2) magnetite, grunerite, stilpnomelane, minnesotaite, chlorite, siderite, and chert, (3) hematite, goethite, martite, specularite, and chert. This paper is primarily concerned with the first facies which is thought to represent the original character of the iron-bearing sediments, the second facies developed from the first by regional and thermal metamorphism, and the third facies is generally considered to be the result of secondary oxidation and leaching.

The original unmetamorphosed and unoxidized facies of the iron formation is present at the surface today only over very limited areas and the rarity of exposures greatly complicates unraveling the depositional history of the iron-bearing formation. One must examine the other two facies and attempt to separate the primary characteristics from those superimposed by later oxidation and metamorphism.

It is generally supposed that the iron was not originally deposited as the oxide and then altered during diagenesis to siderite and iron silicate. Greenalite, common in some districts, seems to be absent or very rare in the Marquette district. A green chloritic mineral which appears to be aphrosiderite is interlaminated with chert as massive beds in the iron formation of the Crystal Falls, Iron River, Florence, and Gwyn districts. It is not known whether this mineral is a product of diagenetic

alteration of volcanic ash or whether it was formed by metamorphism after consolidation (table 2). Sample number 1 consists of chloritic material selected under the microscope for purity. Samples 2 and 5 are dominantly chlorite but contain some hematite and goethite.

TABLE 2

Chemical analyses of chloritic material from Ravena Pricket Mine, Crystal Falls district.

	1	2	3	4	5
SiO_2	25.10	25.38	25.14	25.68	21.50
Al_2O_3	14.28	13.85	14.83	14.73	16.65
TiO_2	.01	.05	.02	.01	.01
Fe_2O_3	6.24	8.95	10.94	11.50	37.39
FeO	26.01	22.79	23.18	21.29	7.06
CaO	.69	.15	.15	.15	.23
MgO	11.59	12.49	10.65	10.83	4.71
H_2O	11.99	12.69	13.32	14.14	12.93
	95.91	96.35	98.23	98.33	100.48

The upper part of the Negaunee formation is exposed on Jasper Knob in the City of Ishpeming where it is composed of alternating laminae of brilliant red jasper and gray specular hematite. Ninty-four clearly defined alternating laminae of red jasper and specular hematite were counted in a thickness of 11 inches. Jasper laminae are usually not more than 0.3 inch thick and are often composed of numerous finer laminae of a second order separated by thin discontinuous streaks of specular hematite. The first order specular hematite laminae range in thickness to about 0.5 inch and contain second order laminae to the number of about 10 to the half inch. Other first order counts at this locality gave 62 in 7 inches and 144 in 14 inches. The figures show considerable uniformity of thickness of laminae with a range of 8.5 to 13 to one inch. The laminae show great regularity and there is no evidence of collapse or shrinkage.

The chert beds in the central part of the Negaunee formation in the Ishpeming-Negaunee area usually range in thickness from a fraction of an inch to 2 or 3 inches and in some horizons they are several feet thick. The chert beds usually are laminated. The lower 200 to 300 feet of the Negaunee formation usually consist of rather thinly bedded alternatingly laminated chert, siderite or hematite, and argillite. The chert

is usually very fine grained when associated with siderite and the siderite is somewhat coarser grained. Granular and oolitic textures are very rare in the Negaunee formation of the Marquette district and are known in only a few thin zones about 1,000 feet above the base of the formation in the Negaunee area and near the top of the formation in the Republic area. Granular texture is usually associated with wavy-bedded cherts and the rarity of this texture in the Negaunee perhaps accounts for the straight-bedded character of the formation. Grain size in the cherts rapidly increases with the degree of metamorphism and in some cases recrystallized cherts may be mistaken for quartzites. In the grunerite-magnetite facies the grains of the chert have about the grain size of sugar and adjacent to some of the larger diabase sills individual quartz grains to one-half inch in diameter are present.

Clastics are interbedded in the basal part of the Negaunee formation in many places. The uppermost part of the Siamo east of Negaunee is a green, red, or black argillite which gradually becomes interbedded with the ferruginous cherts at the base of the Negaunee and 20 to 30 feet of ferruginous chert are present in the Siamo 50 to 75 feet below the top of the argillite. Longitudinal sections in the Mary Charlotte Mine southeast of Negaunee show that argillite interfingers and then passes laterally into the ferruginous cherts of the Negaunee. An interesting feature is the occurrence of quartzite dikes 1/4 to 6 inches thick in the Negaunee at the Empire Mine.

North and west of Palmer at the Maitland and New Volunteer mines a clean to argillaceous quartzite with numerous lenses of conglomerate is interbedded with the Negaunee and may be found hundreds of feet above the base of the formation. Quartzite beds and lenses of rounded, white quartz pebbles of which some are 3 or more inches in diameter are present at least 50 feet above the base of the formation at the Maitland Mine. Some beds are more than a foot thick.

Thickness of stratigraphic equivalents.—The thickness of the Negaunee formation ranges from zero to more than 1,000 feet. Maximum thickness is in the Ishpeming-Negaunee region where it may be 2,000 feet or even more. W. A. Seaman's (1943, plate 4) recent estimate of 400 feet seems to be based on field work in the western part of the district and is certainly not

applicable to the Ishpeming-Negaunee area. Van Hise and Leith (1911, p. 264) assumed that the variation in thickness of the formation was due to erosion prior to deposition of the Upper Huronian. This assumption is not valid as there is no good evidence showing that the Negaunee was deposited with approximate uniform thickness over the entire Marquette district. A fundamental tenet of sedimentation is that in any area of deposition, the lithic units not only do not have uniform thickness but also are not deposited over an entire basin; each thickens and thins and passes laterally into other lithologies. The lateral gradation of the Negaunee formation into muds and sands indicates that the siderite-chert deposits were not only thinner in some places than in others but also that locally no such deposits were made. It is reasonable to assume that many of the differences in thickness are original.

The Vulcan formation of the Menominee district and the Ironwood iron-formation of the Penokee-Gogebic district are usually correlated with the Negaunee. These formations should not be considered exact time equivalents, but equivalent only in the sense that they hold about the same position in the Huronian succession. It seems very likely that deposition of the iron-bearing sediments began and ended in some parts of the Upper Michigan area earlier or later than in some other parts.

Relations to adjacent formations.—The Negaunee formation grades vertically and laterally through transitional lithologies into the Siamo formation. The latter formation is largely absent on the southern limb of the syncline and the Negaunee grades downward through increase of clastics into the Ajibic quartzite. The overlying Goodrich formation has unconformable relations with the Negaunee.

Environment of deposition.—The conditions which led to the deposition of the iron-bearing sediments are by no means fully understood. The abundance of clastics among which are gravels interbedded with the lower part of the Negaunee formation at the Maitland Mine northwest of Palmer indicates shallow waters and current velocities competent to bring materials as large as cobbles to the areas where the siliceous iron-bearing sediments were being deposited. The Negaunee is interbedded with the Ajibic on the southern limb of the syncline

and also interbedded with the Siamo in the area southeast of Negaunee. This situation suggests that the quartzite that has been correlated with the Ajibic on the southern side of the Marquette district is the time equivalent of the Siamo and the Siamo, at least in part, is the lateral equivalent of the Negaunee. It seems certain that the sediments composing the Negaunee formation were being deposited over parts of the area of deposition at the same time as sands and muds of the Ajibic and Siamo were being deposited over other parts and that the three formations have some degree of time equivalence.

It is generally recognized that the siliceous iron-bearing formations are sedimentary deposits but there is no general agreement as to the original sources of the iron and silica. Gruner (1922, pp. 459-460) is of the opinion that the iron and silica were derived through weathering of basic Keewatin lavas, that these were transported by streams and deposited as chemical sediments in a standing body of water. He points out that the Amazon River which carries 3 parts per million of iron could deposit all the iron in the Biwabic formation of Minnesota in 176,000 years.

Moore and Maynard (1929, pp. 275-277) show that normal surface weathering processes can readily provide and that surface waters can readily transport iron and silica to sites of deposition.

Clarke states (1924a, pp. 275-277) that the Mississippi River delivers 136,620,000 tons of dissolved solids annually to the Gulf of Mexico of which .13 per cent is Fe_2O_3 and 7.05 per cent is silica. The quantity of iron transported by the Mississippi River would certainly be many times greater if the drainage basin was underlain by basic igneous rocks[1].

The small quantity of clastic sediments in the purer phases of the siliceous iron-bearing sediments has been cited by Van Hise and Leith (1911, p. 504) as evidence opposed to derivation of the latter through processes of surface weathering. This line of reasoning does not seem to be valid as other chemical sediments—limestone, anhydrite, gypsum, and rock salt—often contain little to no clastic materials although these are formed by normal surface processes. The only requirement for deposition of large quantities of relatively pure

[1] It is probable that much of both iron and silica are not in true solution but in colloidal form.

chemical and biochemical deposits is that arenaceous and argillaceous sediments be prevented from reaching the sites where these sediments are being deposited.

Moore and Maynard (1929, p. 277) state that iron and silica are transported by present streams in colloidal form with the iron stabilized by organic matter. The colloids may be flocculated and ferric hydroxide and silica precipitated to make pure deposits if argillaceous and arenaceous sediments are prevented from invading the sites of deposition. These authors (1929, p. 286) have also shown that bands of alternating iron and silica may be produced by differential settling of silica and ferric hydroxide. Formations of siderite or greenalite could have been produced by reduction of the iron hydroxide shortly after deposition if organic matter was associated with the deposited sediments. There is little evidence, however, that organic matter was ever associated with the Negaunee, Vulcan, and Ironwood iron-bearing sediments in sufficient quantities to reduce the iron to the ferrous state. The generally accepted view that silica is largely transported in the colloidal state in natural waters is based largely on the work of Kahlenberg and Lincoln (1898, pp. 77-90). According to Roy's conclusion (1945, pp. 400-401), more recent and reliable chemical evidence indicates that the silica in natural waters is in true solution. However, it is not certain that the test used to differentiate between colloidal and dissolved silica is decisive.

Woolnough (1941, pp. 476-485) has suggested that the Precambrian iron formations were deposited as chemical sediments in isolated basins on a land surface that had reached the final limits of peneplanation. Absence of relief would prevent transportation of argillaceous and arenaceous sediments and the earlier extensive leaching of the soils would leave little calcareous matter for acquirement. The environment suggested by Woolnough does not seem particularly applicable to the Lake Superior iron formations as no deeply leached soils have ever been found associated and, furthermore, the iron-bearing sediments have been shown to be locally interbedded with and grade into fine and coarse clastics on a regional scale.

Siliceous deposits and those of iron are not uncommon in Paleozoic and later sediments, but association of the two varieties of sediments seems to have parted company by the

beginning of Cambrian time. This suggests that in some important respect the Precambrian environments were different from those of later times. Lane (1917, pp. 45-47), Barrell (1918, pp. 34-36), MacGregor (1927, pp. 155-172), and others have suggested that the early Precambrian atmosphere contained large quantities of carbon dioxide and was low or deficient in oxygen. With this type of atmosphere the weathering product of iron minerals would have been iron carbonate and not iron oxide and the streams could have readily transported the iron in the form of carbonate which would have been precipitated by chemical and biochemical agencies and processes as siderite. Transportation and deposition of silica would not necessarily have been affected.

Van Hise and Leith (1911, pp. 506-510) have called attention to the association in time and place of the Precambrian iron-bearing formations with basic volcanics and have suggested that the iron and silica were either contributed directly to the sites of deposition in waters of magmatic origin or that the iron and silica were released by reaction of hot submarine lava with sea water. A volcanic source for the iron does not greatly assist in solution of the problem if the atmosphere had its present composition as it has been shown (Behrend, 1936, pp. 323-327) that iron oxide and not iron carbonate is being deposited over the sea bottom near the volcano Santorin in the Aegean Sea where submarine springs in some way connected with the volcano bring iron carbonate to the sea bottom.

Sakamoto's (1950, pp. 449-474) studies of the Manchurian Precambrian iron formations led him to the view that the banded iron and silica deposits of that region were produced by cyclic deposition of colloids of iron and silica due to periodic changes in the pH of surface and underground waters which entered basins of deposition. He classifies the iron formation into two-component and three-component poor ores, the former consisting of alternate bands of ferric oxide and pure chert and the latter with the same bands and an additional band composed of iron carbonate and/or iron silicate. He states the banded iron formations are invariably associated with argillaceous and quartzite sediments which are products of mature weathering. Sites of deposition are assumed to have been shallow paralic lakes under conditions of a monsoon-like climate.

Sakamoto points out that iron migrates in acid environments and is precipitated in neutral or alkaline environments, whereas silica migrates in alkaline environments and is precipitated in acid environments. Surface and shallow underground waters tend to be acid during wet seasons; deeper underground waters are alkaline. During dry seasons all waters tend to become alkaline. At the time of the wet monsoon the waters of paralic lakes would rise and overflow to the sea and surface and underground waters above the water table would tend to be acid. These acid waters would carry iron into paralic lakes. Loss of water through evaporation combined with limited inflow during the period of the dry monsoon would sever connections of the lakes with the body of water into which they drained and conditions would become essentially those of evaporating basins in a desert region. During periods of low lake levels the deeper underground alkaline waters would seep into the lakes and introduce silica. The pH of the lake waters in the meantime would have changed from acid through neutral to alkaline. In the change from acid to neutral, iron oxide and chert would be formed; from neutral to alkaline, sideritic chert. Return of the wet monsoon would introduce acid waters, raise lake levels, and waters would change from alkaline through neutral to acid. The change from alkaline to neutral would lead to the precipitation of iron silicates, and further change through neutral to acid would result in pure chert. The two-component poor ores would be deposited when lake levels were high, whereas the three-component poor ores would be deposited only over the low parts of the lake basins when lake levels were low. These relations may be shown in tabulated form:

Acid to neutral	Ferruginous chert	Entire lake bottoms	Dry monsoons
Neutral to alkaline	Sideritic chert	Low parts of basins	Dry monsoons
Alkaline to neutral	Iron silicates	Low parts of basins	Wet monsoons
Neutral to acid	Pure chert	Entire lake bottoms	Wet monsoons

Sakamoto postulates that both rain and the earth's surface were warm in the early Precambrian and under these conditions that bentonitic clays with a molecular ratio of SiO_2 to Al_2O_3 of about 4 would be formed in weathering. Bentonitic clays have high adsorptive capacity for alkalies and alkaline earths and probably much of these would have remained with the weathered products. As the earth's surface and the pre-

cipitation became cooler, weathering changed the bentonitic clays to kaolinitic with a molecular ratio of SiO_2 to Al_2O_3 of about 2, and the alkalies and alkaline earths would be released as the kaolinitic clays have low properties of base exchange. Large quantities of silica would concomitantly be released and transported to sites of deposition. Acid conditions favored by high atmospheric content of carbon dioxide and high rainfall would lead to transportation of iron to the same sites of deposition but only during the periods of the wet monsoons. Banded silica and iron deposits would result. Sakamoto postulates that this warm earth and rainfall prevailed but once in the history of the earth and hence after this time the deposition of banded silica and iron deposits parted company. Sakamoto's explanation may be applicable to the Precambrian iron formations of Manchuria but does not seem to meet all the facts in the Lake Superior region, where the primary form of the deposits seems to have been silica and iron carbonate.

The senior author considers Sakamoto's hypothesis regarding the banded siliceous iron deposits as interesting but certainly not applicable to the Precambrian iron formations of the Lake Superior type. According to Sakamoto's concept one would expect to find banded siliceous iron deposits associated with Paleozoic, Mesozoic, and Cenozoic sediments. The complete absence of such an association is eloquent testimony regarding the inadequacy of the theory. An acceptable theory must include and explain the intimate physical association of the banded siliceous iron deposits of the Keewatin with volcanic tuffs and flows.

Sakamoto's hypothesis appears extremely plausible to the junior author in its application to the iron formations of Manchuria. The junior author does not accept the idea that there was close connection between volcanism and the deposition of iron carbonates and chert if the atmosphere had anything like its present composition. There would have been much deposition of iron oxide and, if the atmosphere had high content of carbon dioxide and low oxygen, resort to magmatic or volcanic waters to acquire the iron carbonate would not have been necessary as iron bicarbonate would have been as abundant in solution as calcium and magnesium bicarbonates. Furthermore, if volcanism in any way was responsible, it would

seem that similar iron and silica deposits would have been made in the later geologic periods during the many times of extensive volcanic activity. The junior writer is of the opinion that there was some environmental factor in the Precambrian periods that was unique to those periods. It is suggested that this factor lay in the atmosphere.

Little magnesium or calcium carbonate is associated with the iron carbonate deposits of the Huronian of Michigan. Algae lived during the time and in the place of deposition of the Kona dolomite precipitated the two carbonates and they must have been living when the Huronian iron formations were being deposited. These organisms would have precipitated lime carbonates had such been in solution in the waters in which the iron and silica formations were deposited. It is considered obvious that these waters in which the siliceous siderites were deposited could have contained little magnesium or calcium carbonate and thus must have had no or very restricted connection with the open sea, so that the waters in the basin or basins in which the iron formations were deposited must have had salinity approximating that of the indraining streams, and these could have acquired little lime from the crystalline rocks over which they flowed. In other words, the waters in the Huronian basins of Upper Michigan in which the banded iron and silica deposits were made were soft and similar in character to the waters in the existing lakes of the same region which receive their waters from areas underlain by crystalline rocks. The iron and silica deposits are of fresh water and not of marine origin.

The segregation of the iron and silica into bands seems to be a primary feature of the Precambrian iron formations and indicates some form of cyclic deposition. If the iron and silica were derived from surface weathering of rocks, a pair of laminae may represent a season as suggested by Sakamoto's hypothesis, but if these substances were derived from magmatic or volcanic sources, the periodicity may be related to fluctuating flow from subaqueous springs or periodic eruptions. Forty-seven laminae were counted in 9¾ inches of the cherty iron carbonate in the New Volunteer Mine near Palmer. If a pair of laminae represents a year, the 47 laminae would represent 24 years and a rate of deposition of about 1 inch in 2½ years. If the laminae are related to volcanisms no

regular periodicity can be assumed. The excellent preservation of the laminae suggests one of the following: (1) deposition of the sediment was rapid and mud-eating and burrowing organisms did not have time to work over the bottom sediments, (2) the environment was such that organisms of this kind could not live in the sediments, (3) such organisms had not yet evolved. It is believed that the last is responsible for the excellent preservation, but the second may be the explanation.

Goodrich Formation

Distribution.—The distribution of the Goodrich formation has the form of a westward-facing U with the eastern margin near the city of Ishpeming. The type locality is at the Goodrich Mine southwest of Ishpeming where the basal beds are well exposed.

Lithology.—The Goodrich formation consists of a basal conglomerate overlain by arkosic, argillaceous, and clean vitreous quartzites, and argillite. The basal conglomerate has very great variations in thickness. The quartzites and argillites form the major but least known parts of the formation. In the western part of the Marquette district the formation has been considerably altered by post-Huronian intrusives, and sericite, chlorite, and biotite schists containing garnet, staurolite, chloritoid, andalusite, and tourmaline have been formed. The argillaceous and arkosic quartzites are well exposed in the vicinity of the National Mine south of Ishpeming. The rock there ranges from fine- to coarse-grained, reddish, greenish, or white impure quartzite with interbedded thin discontinuous lenses of conglomerate.

Because of resistance to erosion the basal conglomerate has excellent exposures, among which are those at the National Mine south of Ishpeming, the Goodrich and Saginaw mines southwest of Ishpeming, the Edwards Mine near Humboldt, and the Republic Mine at Republic, Michigan. Exposures of a less spectacular nature are present at the Spurr, Michigamme, New York, and North Jackson mines. The conglomerate consists of poorly sorted, angular to rounded pebbles, cobbles, and boulders of white coarsely crystalline quartz, red jasper, ferruginous chert, pink to light colored granite,

and a dark schistose rock. The matrix is composed of angular ferruginous sand which has been more or less altered to sericite or chlorite quartz schist. Boulders of the white, coarsely crystalline quartz are abundant at the Republic and Edwards mines, but are rare at the National Mine. White quartz pebbles are usually well rounded; ferruginous chert and jasper fragments derived from the Negaunee formation are angular. Rounded white quartz boulders up to 2 feet in diameter and very large angular blocks of ferruginous chert and jasper are present in the conglomerate at the Republic Mine.

Thickness and stratigraphic equivalents.—The thickness of the Goodrich is obviously variable, but it is difficult to determine as the upper part has little exposure. Van Hise and Leith (1911, p. 265) estimated that at the Goodrich Mine the thickness may be as much as 1500 feet, but state that this is probably much beyond the average for the district. The basal conglomerate varies greatly in thickness over short distances parallel to the strike. It appears to be between 200 and 250 feet in the vicinity of the Edwards Mine and about 300 feet at the Saginaw Mine. It is at least 50 feet thick at the Parsons Pit at National Mine, over 200 feet in a road cut near Humboldt and ranges from 5 to 200 feet in the vicinity of Republic.

The Goodrich formation had not been correlated with any specific stratigraphic unit in other Michigan districts. The unconformity at the base of the Goodrich has been correlated by Leith, Lund and Leith (1935, p. 13) with the unconformity at the base of the Tyler and Copps formations of the Penokee-Gogebic district. Pettijohn (1946) postulates that an unconformity exists between the iron formation and the Upper Slate series of the Crystal Falls district, and correlates this unconformity with that at the base of the Goodrich formation. He states that the basal member of the Upper Slate series, which he considers Upper Huronian, is a graywacke and/or chert breccia that accumulated on the eroded surface of the iron formation which in turn is correlated with the Negaunee. This chert breccia is excellently exposed on Paint River at Crystal Falls, especially in lots 4 and 5 of Sec. 20, T. 43 N., R. 32 W. He states, "The sharp contact with the underlying iron-formation and the great concentration of chert fragments—obviously derived from the iron forma-

tion—are evidence that this deposit is a variety of basal conglomerate indicative of an unconformity." He further states that the relations at this locality ". . . . leave almost no doubt concerning the origin and stratigraphic position of these beds." The authors do not agree that the chert breccia is indicative of an unconformity. The rocks consist of massive graywackes interbedded with chert and the latter is present as regular beds of uniform thickness that pass abruptly into chert breccias. The breccia is composed of angular fragments of chert which are 3 to 6 inches in length by ¼ to 2 inches thick set in a chert matrix. There is no evidence of shingling which might be indicative of current deposition and no other kinds of fragments are present. The graywacke layers contain thin chert beds which also pass abruptly into a rock composed of relatively small angular fragments of chert in a graywacke matrix.

The chert breccias are interpreted by the authors to be of dynamic origin. Probably Pettijohn was influenced by the fact that the chert breccias lie at a general stratigraphic horizon, but this is exactly what would be the case if the breccias were of dynamic origin for movement would be concentrated in the transitional zone between the more competent underlying iron formations and the less competent slates and graywacke slates above.

Very similar features are exposed on Skillet Creek in Sec. 14, T. 47 N., R. 6 E. of the Baraboo district in Wisconsin where the Baraboo quartzite passes upward through a transitional zone into the Seeley slate. The relatively thin beds of quartzite interbedded with slate in the transitional zone are extensively brecciated. Movement during the folding of the quartzite-slate sequence was concentrated in the transitional zone at the top of the thick, competent Baraboo quartzite. Large well-rounded "boulders" of quartzite are present in the transitional zone. These are boudins and they may be seen in all stages of formation. Chert breccias identical to those of the Crystal Fall-Paint River area are not uncommon. They have been seen by the authors in the Negaunee and Bijiki iron formations of the Marquette district, the Ironwood formation of the Penokee-Gogebic district, the Gunflint formation of the Loon Lake district of Ontario, the banded silica rocks of the Michipicoten district of Ontario, the iron

formation of Labrador, and the chert of the Franciscan formation of California. Chert is by no means a competent rock, is relatively brittle, and commonly fails by brecciation.

Relations to adjacent formations.—The Goodrich formation, in general, has unconformable relation with the Negaunee but grades upward into the overlying Greenwood formation. The locally extensive development of coarse conglomerate lenses at the base of the Goodrich marks this horizon as the most spectacular unconformity in the Marquette district. Van Hise and Bayley (1897, pp. 334-335) concluded that there had been considerable orogenic movement as well as deep erosion in post-Negaunee and pre-Goodrich time. They state that the discordance of the two formations is usually not more than 5 to 15 degrees, but cite the Goodrich Mine as a locality where an angular discordance of 90 degrees may be seen. They do not state, however, that the places that show the marked angular discordance are small in scale or that the basal conglomerate is extensively sheared at the Goodrich Mine. The present exposures at the Goodrich Mine do not indicate any marked discordance between the Negaunee and Goodrich formation. Shearing along the contact of the two formations in post-Goodrich time probably accounts for the minor discordance that may be seen. The locally thick conglomerate perhaps gives undue emphasis to the unconformity.

The broad relations between the Negaunee and Goodrich formations are by no means clear. The two formations seem to be conformable in places either with a sharp break in lithology or through a transitional zone; in other places a disconformity is present with little to much conglomerate at the base of the Goodrich. The extent of erosion of the Negaunee formation prior to deposition of the Goodrich does not appear to have been great.

The conglomerate at the base of the Goodrich is in the form of lenses which are relatively thick (220 to 300 feet) locally, but thin rather rapidly along the strike. The coarseness, the extremely poor sorting, and the local distribution of the thick lenses has led students to suggest considerable local relief on the post-Negaunee—pre-Goodrich surface. But so far as the authors are aware no evidence of marked local relief has been seen on the upper surface of the Negaunee and

the discordance of the Negaunee and Goodrich that has been noted as in the vicinity of the Goodrich Mine may be more apparent than real. The thinning of the Negaunee westward in the Marquette district has been cited as evidence of deep erosion, but it is equally reasonable to refer this to depositional thinning in a westward direction.

The relations of the Negaunee and Goodrich formations in the Republic trough are of much interest. At the Kloman Mine northeast of the village of Republic the two formations appear to be essentially conformable. The following descending section shows the lithology and the character of the contact.

Zone	*Feet*
11 Quartzite, fine-grained, massively-bedded with thin laminae, gray. Scattered white quartz pebbles up to ½inch in diameter in top layer	70
10 Concealed	38
9 Quartzite, gray. Contains some iron oxide and ferruginous chert pebbles up to an inch long and ½ inch thick which lie parallel to the bedding. No white quartz pebbles	14
8 Quartzite, gray, sugary	0.75
7 Quartzite, contains thin pebbles of ferruginous chert and red silty quartzite oriented parallel to the bedding. Pebbles range in size up to 2 inches long and ¼ inch thick	4
6 Quartzite, gray, sugary, perhaps recrystallized chert	1.5
5 Specular hematite and clastic quartz. This zone contains fragments of jasper up to 1.5 inches long and 0.5 inch thick oriented parallel to the bedding	2.3
4 Quartzite, gray, sugary, perhaps recrystallized chert	0.75
3 Iron formation (Negaunee). Largely specular hematite in upper portion and interlaminated hematite and jasper in lower portion. Clastic quartz and angular ferruginous chert fragments in upper 4 inches	8.5
2 Iron formation (Negaunee). Repetition of stratigraphic zones of interlaminated specular hematite and jasper with zones of interlaminated white to gray chert and magnetite. The jasper and gray chert laminae are ¼ to 1 inch thick, the hematite and magnetite laminae are ⅛ to ½ inch thick. The thickness of each lamina of specular hematite or magnetite is somewhat proportional to the width of adjacent lamina of jasper or gray chert. Lamina counts range from 30 to one foot to 73 in 3 feet	92.
1 Iron formation (Negaunee). Interlaminated white to gray chert and magnetite	50

About 100 feet to the southeast along the contact, zones 4 to 7 of the above section consist of 10 feet of conglomerate composed of small angular fragments of ferruginous chert

associated with rounded white quartz pebbles which range to an inch in diameter. Many of the ferruginous chert fragments lie parallel to bedding. The contact cuts across 2 to 3 feet of ferruginous chert.

Very spectacular exposures of the Negaunee-Goodrich contact are exposed at the Republic Mine. These have been studied by many geologists. Brooks (1873, plate 6) was the first to map the detailed relations of the Goodrich and Negaunee formations of this area. He mapped a tongue of quartzite branching from the Goodrich formation and extending northwesterly along the face of the Republic Bluff with a thin wedge of jasper intervening between the main body of the Goodrich formation and the tongue of quartzite. Wadsworth (1880, pp. 34-35) examined the quartzite tongue and stated that it was an altered granite dike intruding the jasper, but he later (1893, pp. 129-130) identified the rock in the tongue as quartzite and explained the peculiar relations on the assumption that the wedge of jasper was deposited later than the quartzite and thus was related to the Goodrich formation rather than the Negaunee. Smyth (1894, pp. 680-691) concluded on the basis of detailed surface and underground mapping that the interbedded relation of the quartzite tongue and the jasper wedge was apparent and was due to a fault that repeated the Goodrich-Negaunee contact. He suggested that the fault passed through a breccia zone at the base of the quartzite tongue, and represented the relations in both plan and section (1894, pp. 683-687).

The quartzite tongue on the northern flank of the Republic Bluff is about 4 feet thick and grades downward through a thin interbedded zone of quartzite and jasper into the Negaunee formation. The upper foot of the quartzite contains considerable specular hematite and passes conformably upward into the overlying jasper. There is absolutely no evidence of faulting. Traced southward along the Republic Bluff the basal contact of the quartzite tongue shows a distinctly disconformable relationship with the underlying Negaunee jaspers. The writers agree with the Wadsworth view that the quartzite tongue is conformable with the overlying jasper. The conglomerate at the base of the Goodrich at Republic Village consists of angular blocks of the Negaunee iron formation in a quartzite matrix. Some blocks are very large—up

to 20 feet long and wide and a foot thick—and consist of flat slabs of the iron formation that have been tilted or moved only short distances. Other excellent exposures of the Goodrich conglomerate are in the vicinity of the West Republic Mine near the Michigamme River where white vein quartz pebbles, cobbles, and boulders up to 2 feet in diameter are associated with subangular to angular blocks of iron formation. Sorting is very poor and the conglomerate lens appears to attain a thickness of 200 to 300 feet. It thins rapidly to the northeast and at the Republic Mine about a quarter of a mile distant the thickness is only a few feet.

Environment of deposition.—The local abundance of coarse clastics and the poor sorting shows that the sediments were moved by strong currents and deposition was rapid. Two types of materials are present, of which one consists of well-rounded pebbles, cobbles, and boulders of white vein quartz, granite, and schist, and the other of angular to subangular fragments of the Negaunee iron formation. The first class of materials was transported for considerable distances and then deposited with angular fragments of iron formation of local origin. The conglomerate may represent beach deposits made in a body of water advancing over a land surface underlain by the Negaunee formation, but the poor sorting and lenticular character of the sediments is more suggestive of a deltaic subaerial environment with a close source for the angular materials. The well-rounded particles of quartz, granite, and schist must have been derived some distance from the sites of deposition.

Greenwood Formation

Distribution.—The Greenwood formation is best known on the south limb of the Marquette syncline where it was traced continuously by Swanson (1930) from a point 3 miles west of Ishpeming to the vicinity of Humboldt, some 15 to 20 miles to the west. The formation apparently is absent, or has not been recognized on the north limb of the syncline except at the Michigamme Mine. It probably passes into the Michigamme formation. The name is from the village of Greenwood on the D. S. S. and A. railroad west of Ishpeming.

Lithology.—The Greenwood formation has been extensively metamorphosed to a magnetite, grunerite, chloritic quartz

rock that closely resembles some of the metamorphic facies of the Negaunee formation. Siderite and chert within some of the thicker beds indicate that these were the original minerals. Many beds resemble quartzite and these were probably chert layers that have been extensively metamorphosed. Some horizons consist largely of chlorite and amphibole and appear to have a tuffaceous texture. These may represent pyroclastics that were a prelude to the extensive activity of the succeeding Clarksburgh. The Greenwood formation has limited exposure, but can be more or less traced by reason of its magnetic character.

Van Hise and Bayley (1897, p. 421) correlated a metamorphosed iron formation at the Michigamme Mine that is separated from the Negaunee formation by a quartzite with the Bijiki member of the Michigamme formation. However, it seems probable that this is actually the Greenwood formation and the quartzite below it represents the Goodrich. The following descending section was measured at the Michigamme Mine.

Zone	*Feet*
5 Iron formation, metamorphosed. Thick-bedded, mostly magnetite with nodules of recrystallized chert up to 6 inches in diameter in upper half and lenses of recrystallized chert in lower portion. Grunerite is conspicuous	25
4 Iron formation, metamorphosed. Thin-bedded, magnetite, grunerite and recrystallized chert	110
3 Iron formation, metamorphosed. Massively bedded, magnetite, grunerite, hematite and recrystallized chert interbedded with quartzite	14
2 Quartzite, massively bedded, grayish to greenish, beds 1 to 3 feet thick (Goodrich)	46
1 Hematite ore zone at top of Negaunee iron formation	6

Thickness and stratigraphic equivalents.—The preceding section shows that the Greenwood grades downward conformably into the Goodrich quartzite. On the south limb of the syncline the formation passes upward and downward into clastic sediments of the Clarksburgh and Goodrich respectively.

Environment of deposition.—The Greenwood iron-bearing sediments seem to have been deposited as chert and siderite and the environment of deposition is considered to have been in a paralic lake on the Greenwood delta. The Clarksburgh volcanics may have contributed to the formation of the lake

basin. Thus, the formation may be equivalent to some part of the Goodrich and also to some part of the Clarksburgh.

Clarksburgh Formation

The Clarksburgh formation is confined to the southern limb of the Marquette syncline and has been traced from a place about 3 miles west of Ishpeming to the vicinity of Champion. The most extensive exposures are at and in the vicinity of the type area southeast of Clarksburgh. The formation thins rapidly to the north and more slowly to the east and west.

Lithology.—The formation is dominantly composed of fine to coarse pyroclastics associated with graywackes and minor quantities of tuffaceous quartzite and marble. A few small lava flows have been recognized. The pyroclastics range from coarse, massively bedded agglomerates to fine-grained thin-bedded tuffs. The marble is present as lenses in the pyroclastics or as matrix to fragments of tuff or agglomerate. About 100 paces southeast of the northwest corner of Sec. 18, T. 47 N., R. 28 W. fragments of quartzite, recrystallized chert, and rounded bodies of granite are present in a matrix of basic fragmental material. Swanson (1930, p. 7) states that this exposure may be a volcanic neck through which a part of the Clarksburgh volcanics were ejected.

Thickness and stratigraphic equivalents.—The thickness of the Clarksburgh ranges from zero over most of the Marquette district to a maximum of perhaps several thousand feet in the area southeast of Clarksburgh. It probably has time equivalence with the lower part of the Michigamme formation and also with parts of Greenwood and Goodrich. Leith, Lund, and Leith (1935, p. 10) correlated the Clarksburgh with the Paint River belt of greenstones of the Crystal Falls and Iron River districts and the south belt of Quinnesec greenstone of the Menominee district. The greenstone agglomerates, tuffs, and flows of the eastern Penokee-Gogebic district hold approximately the same position in the Huronian sections as the Clarksburgh.

Environment of deposition.—The area about Clarksburgh obviously was the center of explosive activity during Clarksburgh time. The well-bedded pyroclastics and the associated

graywackes and calcareous sediments seem to have been deposited in standing water; other parts may have been deposited on land. The calcareous sediments may suggest marine water, but the lime may also have been derived from the weathering of basic pyroclastics.

Michigamme Formation

Distribution.—The Michigamme occupies the central part of the Marquette syncline and forms a belt one to 2 miles wide that extends from about a mile west of Ishpeming to Lake Michigamme and westward. West of Lake Michigamme the formation underlies a large area extending westward to the Penokee-Gogebic district and southward to the Crystal Falls and Iron River district. Northward the formation extends to Lake Superior southeast of Keweenaw Bay. The type locality is on Lake Michigamme where extensive exposures are on the shores and the islands in the lake.

Lithology.—The Michigamme formation consists of argillites, black and green shales, argillaceous quartzite, white vitreous quartzites, graywackes, and an iron-bearing member known as the Bijiki. The formation has been extensively metamorphosed in the vicinity of Lake Michigamme by post-Huronian granite and basic intrusives to form chlorite and muscovite schists, slates, and gneisses with porphyroblasts of garnet, tourmaline, staurolite, andalusite, and chloritoid. The quartzites and graywackes form most of the natural exposures; the slates which compose most of the formation underlie low or flat ground and are rarely exposed. The composition of the formation is seen to best advantage along some of the streams that flow into Lake Superior and there are excellent exposures of all phases of the lithology in Baraga County on Lake Superior on the east branch of the Huron River, Slate River, and South Falls River.

Colors of the argillites and slates range from gray and green to black. The green color apparently is due to ferrous iron minerals and the black to finely disseminated carbon. Argillites containing about 20 per cent carbon have been quarried for graphite in the vicinity of Taylor Mine. Black slates usually contain considerable iron in the form of iron sulphide as disseminated very fine grains or as veinlets and stringers. The iron content of many zones is often of the

same order of magnitude as that of oxidized cherty iron formation.

The Bijiki member seems to be situated some distance above the base of the Michigamme formation. It is not clear whether this iron formation is a single stratigraphic horizon or consists of a series of lenses on several horizons. The oxidized facies may be seen at the Marine, Northhampton, Phoenix, Pascoe, Hortense, and Bessie mines near Champion, and at the Titan, Beaufort, Ohio, Portland, Webster, and Imperial mines west of Lake Michigamme. Where unoxidized, the Bijiki consists of magnetite, grunerite, and recrystallized chert. Siderite is present at some localities. The member ranges from thin- to thick-bedded and is interbedded with black argillites and graywackes at both the base and top. In Baraga County on Lake Superior the Bijiki is composed largely of chert which on the east branch of the Huron River rests unconformably on pre-Huronian granites.

Thickness and stratigraphic equivalents.—Van Hise and Leith (1911, pp. 267-268) state that the thickness of the Michigamme may not be more than 1000 to 2000 feet, or it may greatly exceed these figures. The thickness of the Bijiki member ranges from zero to about 500 feet.

Van Hise and Leith (1911, p. 598) and Leith, Lund, and Leith (1935, p. 10) correlate the Michigamme slate of the Marquette, Menominee, Crystal Falls, and Iron River districts with the Tyler slate of the Penokee-Gogebic district. The Michigamme and Tyler have similar lithologies and hold a similar position in the Huronian sequence. The Tyler formation ranges in thickness from zero to a maximum of perhaps 11,000 feet. The Copps formation of the eastern Gogebic is correlated by Atwater (1938, p. 179) with the Tyler, the correlation being based on similarity in lithology and unconformable relations of both Copps and Tyler with the Middle Huronian iron formation.

Relation to adjacent formations.—The Michigamme grades into both the Clarksburgh and Greenwood formations and is overlain by glacial drift. North of the Marquette district in the vicinity of Silver Lake and on the east branch of the Huron River the formation rests unconformably on pre-Huronian granites and gneisses.

Environment of deposition.—The Michigamme, Tyler, and Copps formations originally were composed largely of sands and muds. The monotonous repetition of sand and mud layers denotes marked fluctuations in the competencies of the transporting currents and the extremely poor sorting shown in much of the sands suggests rapid deposition. The initial deposits of three formations may be visualized as accumulating in a delta environment near the mouths of streams entering the Huronian Basin. This may have and probably did contain fresh water as there is nothing to indicate marine conditions. The lateral growth of each deltaic deposit eventually led to the merging of the several deltas and filling of the basin. This sequence of events produced a deltaic environment of considerable extent. The great thickness of the sands and muds and the transgressive overlap on the pre-Huronian granites and gneisses north of the Marquette syncline indicate progressive subsidence and enlargement of the area of deposition.

The pyrite-bearing carbonaceous argillites and slates of the Michigamme and its stratigraphic equivalents closely resemble the black graptolite-bearing shales of the Paleozoic. It is probable that the bottoms on which the black argillites accumulated during Michigamme time were so fouled by lack of oxygen and by the presence of hydrogen sulphide that no life could exist. Near the surface the waters were apparently suitable to permit some form of planktonic life. Whether both plants and animals lived in these waters is unknown for fossils have never been reported from the Michigamme slate or its equivalents. The abundance of carbon however indicates that some type of life, perhaps microscopic algae, flourished in the surface waters. Black muds high in organic matter are accumulating today in shallow bays with a restricted connection with open water, in fjords with elevated thresholds, and on the deep portions of bottoms of standing bodies of water.

The iron-bearing sediments of the Bijiki member were deposited in clear waters in areas where sands and muds were not ordinarily brought. Lagoons between distributaries or lakes upon the delta or deltas seem to be the most probable areas of deposition. The presence of siderite and chert in the Bijiki indicates that the origin of these deposits is probably similar to that of the Negaunee iron-bearing formation.

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University of Wisconsin
Madison, Wisconsin

ESSAY REVIEW

Deciduous Forests of Eastern North America; by E. Lucy Braun. Pp. xiv, 596; 95 figs., 90 tables, map. Philadelphia and Toronto, 1950 (The Blakiston Company, $10.00).—The publishers of this admirable book, not content with setting a price that takes it well out of the field-manual range, have decreed that "no dramatization in lectures or radio is allowed." This is a pity, for it tells an absorbing story. As drama, the account of the post-Jurassic development and present deployment of the major assemblages of deciduous trees in North America east of the prairie and south of the taiga owes more to Shakespeare's historical pageants than to Broadway; it is weak in sex appeal and comic relief, but strong in process and the analysis of character. The result of years of observant travel and intensive study on the part of its author, the book makes a brave attempt to see in its entirety the nature of a plant formation that is second only to equatorial rain forest, among the terrestrial formations of the world, in the taxonomic complexity of its make-up.

In a deceptively subdued beginning, Miss Braun states with clarity and succinctness the ecologic principles governing the classification of forest communities, and shows commendable restraint in using a small number of technical terms endowed with a reasonable amount of meaning. She then describes, in detail, but without confusion, the nine major climax association-types and their principal subordinate associations that collectively make up the Deciduous Forest Formation. The nine regional climaxes do not entirely coincide with those discerned by previous workers; Miss Braun makes a powerful case for her scheme, and it seems likely to endure. Certainly few ecologists have the requisite experience and knowledge to challenge it. The regional climaxes are plotted on a folded-in map (essentially the same as Lobeck's "Physiographic Diagram"), a linen-mounted version of which can be purchased separately for $1.50.

An invaluable feature of the descriptive presentation is the inclusion of many tabular lists, arranged by percentage composition, of tree species found in particular "stands." Stands are concrete illustrations of the abstract associations recognized, and from their careful description and from the numerous well-chosen photographs the layman can find out what kind of forest is meant. To gain this advantage, which non-botanical users of this book will find inestimable, Miss Braun has had to sacrifice some "objectivity." That is, she has chosen to ignore the elaborate statistical procedures of phytosociology. Those who insist on the distinctions between "frequency," "density," and "constancy" will be horrified at the use of so elementary a statistic as percentage

composition, but it does preserve for the ordinary reader the true character of a patch of vegetation. Miss Braun's description of vegetation has an old-fashioned flavor, as her common sense is an old-fashioned virtue.

The reviewer is less happy about some other aspects of the old-fashioned viewpoint so delightfully maintained in this book. In brief, he has the feeling that the work represents the end of an era of ecologic thought. The descriptive phase, the culmination of the tradition of Cowles and Clements, is essentially complete; where does it bring us? One may hope that it brings the ecologist to the point where he can begin to study community metabolism, to discover rates of change of energy in different climaxes and in successional stages leading up to the climax. If so, no hint of how to proceed can be found in this work; in her preoccupation with establishing criteria for recognizing a climax when one sees it, the author fails to discuss what happens in a climax after it is attained.

This is probably not a fair criticism, for "Deciduous forests of eastern North America" is not a work of ecology, but of plant geography; the distinction is becoming increasingly clear. Earth scientists, at least at present, are little concerned with the dynamics of eco-systems, which is the main business of ecology. They are much concerned with distribution patterns among plants and among communities, and they will value Miss Braun's book as a major contribution to this subject. Climate and topography are the twin controls of forest distribution; topography, and climate to a certain extent, are modified by vegetation, and physiographic and vegetational evolution have gone hand in hand. In discussing this evolutionary process, to which Part III of the book is devoted, Miss Braun is handicapped by the fragmentary nature of the paleobotanic record. Accordingly she turns to present-day phytogeography, particularly to relict occurrences and other forms of disjunct distribution, for her evidence. The result is an ingenious, stimulating, and highly hypothetical account, according to which the nearest approach, among the surviving association-types, to a lineal descendant of the Tertiary mixed forest is the Mixed Mesophytic Forest of the non-glaciated southern half of the Appalachian Plateau; restriction of its most typical examples to places where the Schooley peneplain was never perfected is regarded as especially significant.

The reviewer has stated elsewhere a number of minor objections to Miss Braun's view of the vegetational history of southeastern United States; they add up to the single objection that such a view seriously underestimates the ability of plants to spread. But the evidence of past geographic conditions derived from present-day

distributions is altogether too tenuous to warrant polemics. Miss Braun has stated her case, and stated it well. If it is destroyed or radically modified, it will not be by argumentation, but because new evidence from fossils comes to hand. Meanwhile her thesis deserves thoughtful consideration by geographers of all sorts.

E. S. DEEVEY

REVIEWS

Text-book of Modern Pollen Analysis; by KNUT FAEGRI and JOHS. IVERSEN. Pp. 168; 14 figs., 9 plates. Copenhagen, 1950 (Einar Munksgaard, Dan. kr. 16.00).—This is an extremely useful and on the whole sensible manual of methods in pollen-statistical research. Its authors are two of the ablest workers the field has yet produced, Iversen in particular being the "botanist's pollen analyst"—i.e., the leading expert in the identification of the relatively infrequent pollen grains of non-arboreal species whose importance in postglacial stratigraphy is being given increased recognition. Unfortunately, this kind of *expertise* cannot be learned from a book, and except for a general chapter on pollen morphology and a key to pollen types applicable only in northwestern Europe, the manual devotes itself to matters other than identification: field technique, chemical processing of samples, drawing up of pollen diagrams, stratigraphic sections, and maps, and sources of error. Much of the advice can be applied without modification in North America; much, alas, cannot, but this is mainly the fault of the backward state of the science as practiced in America, and not of the authors.

E. S. DEEVEY

Einführung in die Gesteinskunde; by H. LEITMEIER. Pp. viii, 275; 100 figs. Vienna, 1950 (Springer-Verlag, $4.40).—As explained by the author, who is professor at the University of Vienna, he was urged and encouraged to write this book because for more than twenty years no elementary book on petrography designed for the beginning student has appeared in the German language. The fourth and final edition of Rosenbusch's classic *Elemente der Gesteinslehre* was published in 1923 and Rinne's *Gesteinskunde,* a book of somewhat wider scope and more elementary nature than the Rosenbusch volume, last appeared in 1928. The original intention of the author was to write a *Lehrbuch,* but in order to keep the price of the book within reasonable bounds, much of the material assembled was omitted and the present Introduction to Petrology was produced.

The systematics of the igneous rocks is essentially that of Rosenbusch, somewhat simplified. The mode of presentation differs

however, in that Leitmeier begins with the basalt family, follows it with the corresponding plutonic gabbro family, and so on, ending with the liparite-quartz porphyry family and its plutonic equivalent, the granite family. The igneous rocks are concluded by an account of the genesis of the granitodioritic rocks (pp. 125-128). It is somewhat surprising that the antiquated German custom of giving one name to a Tertiary rock and another to its pre-Tertiary equivalent has not been abandoned.

The sedimentary rocks are described under the two major groups —clastic sedimentary rocks and chemical sedimentary rocks. This grouping is recognized to be logically unsatisfactory, however. The metamorphites (a term proposed some years ago by K. H. Scheumann) are divided into two groups: contact rocks and crystalline schists.

The final class of rocks described comprises the mylonites. The mylonites are considered not to be members of the crystalline schists but to comprise rocks characterized by a condition of strong mechanical deformation which has greatly altered the original rocks so that they have taken on new external aspects.

The book is well printed and is attractively illustrated.

ADOPLH KNOPF

Geometrische Kristallographie und Kristalloptik und deren Arbeitsmethoden; by FRANZ RAAZ and HERMANN TERTSCH. Pp. x, 215; 260 figs. Vienna, 1951 (Springer-Verlag, $4.50).—The second edition of this short text will receive wide recognition for its concise treatment of practical geometrical and optical crystallography. The organization of material is conventional enough to need no detailed outline. Professor Raaz treats crystallography (123 pages) under such headings as basic laws, symmetry, classes, forms, twinning, and structure. Professor Tertsch considers optics (85 pages), first in general, then specifically with respect to crystals, the polarizing microscope as orthoscope and conoscope, optical activity, anomalies. The text is well written and clear. No attempt is made to develop the complete theory at any point (references to standard texts would permit a superior student to fill in here if necessary) but enough theory is given to permit understanding the practical methods described. The book fulfills its authors' purpose to present the subject in a way that will be useful to the research worker in related fields, who cannot afford the time for a complete understanding of crystallography and optics, but should know their possibilities for his own field. The conciseness of the book is the only possible objection; this would be compensated by lectures and accompanying laboratory instruction. HORACE WINCHELL

Crystal Growth; by H. E. Buckley. Pp. xv, 571; 169 figs., 88 plates. New York, 1951 (John Wiley & Sons, Inc., $9.00).—The author has gone to considerable lengths to present the reader with all the important details relating to the growth of crystals. The problems of solubility, supersolubility, dissolution, and solution are dealt with in regard to the general problem of crystal growth and with respect to the specific laboratory problems. Not only are all the familiar methods of crystal growth presented, but a host of the techniques known only to the specialist are described. The closing chapter, on the peculiarities of crystals, is interesting reading and presents a wealth of unusual information. Excellent references at the end of each chapter should prove valuable to anyone desiring additional information.

Those sections relating to crystal theory are well handled; enough detail is given to make possible understanding of the methods, but not so much as to prove boring. In particular, more recent crystal theory is excellently presented. Fine plates of actual crystals and good drawings illustrate the concepts well.

This book will be of interest to anyone interested in crystallography: novices will find it fascinating, and not too difficult; those who are engaged in the work professionally will find complete discussions of most phases of the work, including laboratory notes. The descriptions of equipment, along with fine illustrations, enable one to grasp the methods and, if desired, reproduce the tests. The book presents a good coverage of all aspects of crystal growth.

B. E. GRIFFIN

Guide to Geologic Literature; by Richard M. Pearl. Pp. xi, 239. New York, 1951 (McGraw-Hill Book Company, $3.75).—Here at last is *the* book for the research geologist. Not to be misled by the title, however, this is not a book on geology, but rather a guidebook to the literature of geology. No account is found of the development of any of the geological journals, nor are any of the conventional periodicals listed. Instead, reference is made to the "Directory of Geological Material in North America" (A. A. P. G., Bull., vol. 30, no. 8, pt. 2, pp. 1323-26, 1946). As a reference book, it serves well the geologist, geographer, cartographer, and librarian.

The book is divided into three parts. An introduction points out the problems found in the literature and in conducting the search. The second part is on library facilities, and the third on the kinds of geologic literature. The information presented is cross-referenced throughout the book. A worldwide directory of 119 scientific publishers and services provides a selected list for the searcher. The index is 27 pages in length.

A reference librarian will welcome this book. It may mean that geologists will be able to approach their problems of literary research with much more understanding. For instance, Pearl explains the portions of the Dewey decimal system and the Library of Congress system of classification of books that deal with geology. The classic indexes of geologic literature are recorded, and author index and subject index problems simplified. Of the 25 libraries in the United States listed with the most important collections of geologic publications, 17 are in university libraries. The remainder are in private or government libraries; no college libraries are listed. Twenty-seven library collections most important for geographic research are enumerated. Services on photoprinting, microfilming, and on translations are clarified.

The remaining 80 percent of the book is concerned with index guides and bibliographies, abstracts, periodicals, United States government documents, organization bulletins, state bulletins, county and city bulletins, bulletins of foreign countries, books, newspapers, theses, unpublished manuscripts, and maps. American librarians have indexed and compiled bibliographies among their own library holdings. Fifteen libraries have special indexes represented under the headings: geology, geography, paleobotany, and mining. Published bibliographies include those in general geology, seismology, geography, mining, and general science and technology, including geology.

A discussion on the value of abstracts as guides to the literature introduces the subject of abstract journals in general geology, economic geology, geophysics, ground water, mineralogy, mining, petroleum, and coal. As the periodical is an important medium of expression in geology, library research in periodicals is stressed. The periodicals of value to a geologist are listed in general lists, library lists, union lists, and index guides to scientific and technical periodicals.

United States government documents pertaining to geology are found under their respective departments: Interior, Bureau of Mines, Agriculture, Commerce, and in independent offices and quasi-official agencies. A directory of state geologic surveys tabulates all states with a survey of some nature, except Delaware, Massachusetts, and Utah (although Massachusetts has a cooperative project between the Massachusetts Department of Public Works and the U. S. Geological Survey). There is a directory of 42 state bureaus of mines. County and city publications are included, although relatively insignificant. Concluding a chapter on other countries is a directory of 73 foreign geologic surveys. A miscellaneous category exists for publications that "do not belong in the

other chapters of this book." Pearl pigeonholes these into a chapter on books. He discusses review series, reference books, book reviews, book abstracts, and lists of new, selected, and old books.

United States government maps are issued by the Geological Survey as indexes and catalogues, and by other agencies, such as the Army Map Service, Coast and Geodetic Survey, Bureau of Land Management, the Forest Service, and the National Park Service. Organization maps include those by the well known geological and geographical societies. Catalogues of maps published by foreign countries are described. Commercial maps and aerial photographic maps complete the discussion.

Despite the fact that the advance of geology as a science is slow, this book will help the researcher hasten its progress. The best judge of such a book, of course, is its usage. Although the book tells the research geologist most of what he already knows, it will prove invaluable to the new researcher and to other scientists probing into geology for their first adventure. Such a book has long been needed—a guide, which will point the way towards well-founded research. SIDNEY E. WHITE

Soils of the Netherlands; by C. H. EDELMAN. Pp. 184, illustrated. Amsterdam, 1950 (North-Holland Publishing Company, 17.50 flo.). —In 177 pages of text, Edelman presents a concise statement on the morphology, genesis, and geography of the soils of Holland. The book not only proved exceedingly useful as a guide for the use of delegates to the Fourth International Congress of Soil Science (Amsterdam, 1950), but is the best English-language summary of the soils of the Netherlands available today.

The book has 14 short chapters dealing with the following subject matter: General description of the Netherlands; classification of Dutch soils; sandy soils; river clay soils; peat and reclaimed peat soils; dune-sand soils; marine "clay" soils of four important regions; estuary soils; Zuiderzee-bottom soils; soils of the reclaimed pools (Droogmakerijen); and the loess-loam soils.

It is clear that Dutch pedologists have had to make the most careful studies of sedimentation, Pleistocene and Recent stratigraphy, archaeology, and plant ecology, in order to gain the information required for reclamation of land for cultivation. Soil classification in areas reclaimed from peat bogs, from river flood plains, and from the sea is based primarily on texture and structure of sediments, mineral composition, the kind and amount of organic matter, and features of the soils that owe their characteristics to man's activities. Forested soils above sea level are recognized by such generally used names as "Brown Earths" and "Podzols."

Throughout the book one is impressed with the importance of man as a major factor in soil formation.

The book is well printed, and illustrated with 65 figures, including many line drawings and several half-tone photographs.

A Provisional Soil Map of the Netherlands, scale 1 inch = 10 km., and in 55 colors gives an excellent idea of the kinds of soils and their geographic distribution. JAMES THORP

The Chemical Elements and Their Compounds; Vols. I and II; by N. V. SIDGWICK. Pp. xxxviii, 1703. Oxford and New York, 1950 (Oxford University Press, $14.00).—To quote from the preface, this work "is an attempt to discuss in detail the properties of the elements and their compounds in the light of modern ideas of atomic and molecular structure." The introductory chapter of about twenty pages covers atomic and molecular structure and the periodic classification in a brief but lucid fashion. The rest of volume one is devoted to the first five groups of the periodic classification. Volume two covers groups 6, 7, and 8.

The volumes are not in any sense a complete compendium of inorganic chemistry, but rather an appraisal of the main outlines of the subject from the point of view of newer theoretical advances. One of the unusual features is the inclusion of many compounds usually considered a part of organic chemistry. This undoubtedly is of great value, as it will help to break down some of the modern prejudices arising from excessive division of chemistry into a number of mutually exclusive compartments. The reader gets a far more unified picture of "Chemistry" than is possible with most texts. All this is accomplished in the fine style we have come to associate with Professor Sidgwick. There are numerous examples of the author's flair for illuminating a subject. For example, in discussing the surprising existence of liquid helium at the lowest temperatures, he says, "it is really no more surprising than that a hydrogen atom at the absolute zero should have its electron in the first quantum state and not in the nucleus."

The 1666 references cover the literature up to 1948. Diagrams and graphs are not numerous, but tables are plentiful. There are adequate subject and author indices (at the end of vol. 2).

There are also a few inevitable errors, such as the statement that chromium carbonyl can be sublimed without decomposition at 160°. The work of F. O. Rice is mentioned only once in the discussion of free radicals.

These shortcomings, however, are minor compared to the success achieved in presenting a fresh, unified interpretation of inorganic chemistry. We should all be grateful. V. GILPIN

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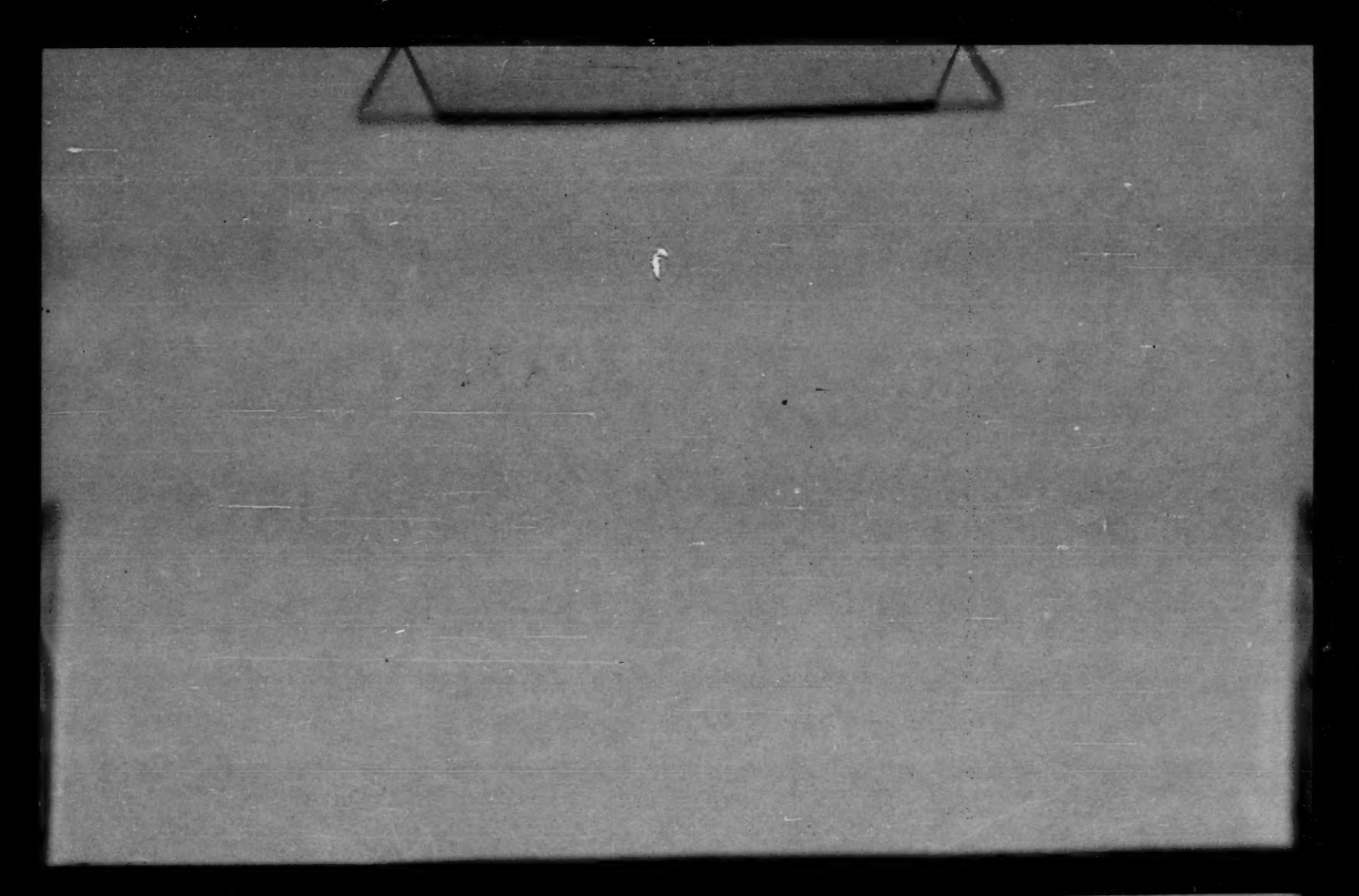

VOL. 250 No. 2, 1952

CONTENTS

MOUNT GARIBALDI, A SUPRAGLACIAL PLEISTOCENE VOLCANO IN SOUTHWESTERN BRITISH COLUMBIA ..*W. H. Mathews* 81

THE ENDOGENIC ENERGY OF THE EARTH *R. W. van Bemmelen* 104

SEDIMENTATION AND STRATIGRAPHY OF THE HURONIAN OF UPPER MICHIGAN, PART 2 *S. A. Tyler and W. H. Twenhofel* 118

ESSAY REVIEW

Deciduous Forests of Eastern North America; by E. LUCY BRAUN *E. S. Deevey* 132

REVIEWS

Text-book of Modern Pollen Analysis; by KNUT FAEGRI and JOHS. IVERSEN *E. S. Deevey* 134

Einführung in die Gesteinskunde; by H. LEITMEIER .....*Adolph Knopf* 134

Geometrische Kristallographie und Kristalloptik und deren Arbeitsmethoden; by FRANZ RAAZ and HERMANN TERTSCH .....*Horace Winchell* 135

Crystal Growth; by H. E. BUCKLEY .....*B. B. Griffin* 136

Guide to Geologic Literature; by RICHARD M. PEARL .....*Sidney E. White* 136

Soils of the Netherlands; by C. H. EDELMAN .....*James Thorp* 138

The Chemical Elements and Their Compounds; Vols. I and II; by N. V. SIDGWICK .....*V. Gilpin* 139

Publications Recently Received 140

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